ANGULAR MOTION INSTRUMENTATION FOR MODEL SEAWORTHINESS TESTING

William R. Porter

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by

William R. Porter
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ABSTRACT

ANGULAR MOTION INSTRUMENTATION FOR MODEL SEAWORTHINESS TESTING

William R. Porter

Submitted to the Department of Naval Architecture and Marine Engineering on 23 May 1955 in partial fulfillment of the requirements for the degree of Naval Engineer.

The purpose of this investigation was to develope an angular motion instrumentation system suitable for ship seaworthiness and ship motion studies. Model testing in the M.I.T. Towing Tank was particularly in view, but full scale field measurements are a possibility.

The system presented was built around a Type H Integrating Gyroscope (HIG). With the HIG in its case are associated several additional units performing service functions, such as temperature control, but requiring only casual surveillance by the operator.

The system presents a continuous time-base record of angular motion or angular velocity of the moving body about an axis parallel to the HIG sensitive axis. One sample record is presented, and reference is made to a concurrent series of measurements separately reported.

The potential for further development is considered to be very great indeed and some discussion is presented for improvement of the present system and also extending performance.

Thesis Supervisor: Martin A. Abkowitz

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TABLE OF CONTENTS

LIST OF FIGURES

I

INTRODUCTION AND SUMMARY

1.1 Objective.

The purpose of this investigation was to develope an angular motion instrumentation system suitable for ship seaworthiness and ship motion studies. The literature indicates an increasing attention to seaworthiness and analysis of ship motions in waves. Appendix A presents a brief appreciation of this subject, with literature references. The M.I.T. Towing Tank is actively engaged in model testing pertinent to performance in waves. Measurements of angular motion – displacement or time derivatives – can be readily appreciated as significant to this testing. Work in this field at M.I.T. is referenced in Appendix A.

Stroboscopic and flash-photography methods of position measurement and manual reduction of this data has been employed prior to this investigation. The photographic method is characterized by these features:

1. The data is sampled at discrete intervals.
2. Data reduction is time consuming and increasingly so as the sampling interval is decreased.
3. Extension of the measurement to the first time derivative to get angular velocity is subject to the usual insecurities of differentiating less-than-ideal data.
4. An experimentally-inconvenient delay between taking of the data and an appraisal of difficulty or success in the run.
5. Not adaptable to full scale testing.

The instrumentation system which is the subject of this investigation is characterized as follows:

1. Provides immediately a continuous time-base record.
2. Requires no data-reduction labor to provide a graphical record.
3. Provides choice of displacement or velocity direct measurement.

4. Maintains sufficiently high accuracy standards to eliminate concern with uncertainties in the recording system for at least most experiments.
5. Simplicity of operation.
6. Sufficiently portable and adaptable to utilize in field tests.
7. Potential for further development.

The system to be described, with the advantages above, is built around the properties and capabilities of an integrating gyroscope. This instrument will be described more fully in Chapter II and Appendices A and C. The instrumentation system will be called the "Gyro Instrumentation System", next described.

1.2 The Gyro Instrumentation System.

The system to be described is shown schematically in Figure I. The equipment is photographed in Figure II. As shown, several units comprise the system. The functional names describe the unit nature. With the exception of the gyro case, which must be in the model, the location of the remaining units is not critical. The arrangement of Figure I is believed to be convenient for a towed-in-waves run. With this arrangement, the slip-connection to the Temperature Control Unit is broken just before a run and the number of wires running into the model is minimized.

The number of units subdividing the system is one of convenience and flexibility. Fortunately the array of units does not imply complexity. Most units require no attention once the system is installed and the initial operating sequence implemented. Attention then may be concentrated on the model itself and the time record issuing from the recorder. Resetting for another recording run may be no more complicated than start-and-stop of recorder chart paper.

1.3 Typical Applications.

In the opinion of this author the potential for applications and for further development of this system are very great indeed. The time that has been allotted this investigation has been spent in design and construction of the pictured units and little time has been

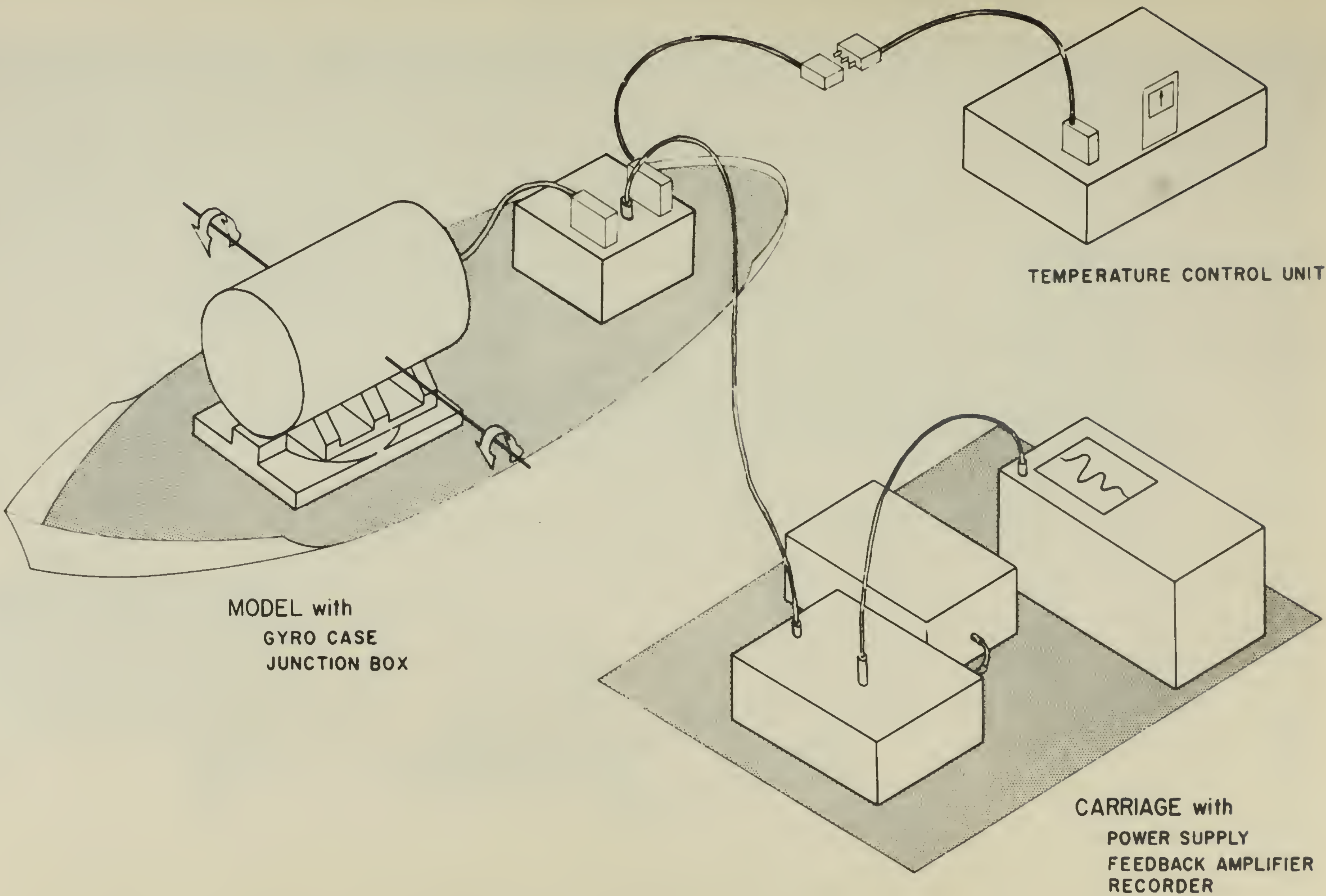


Fig I. Instrumentation System.

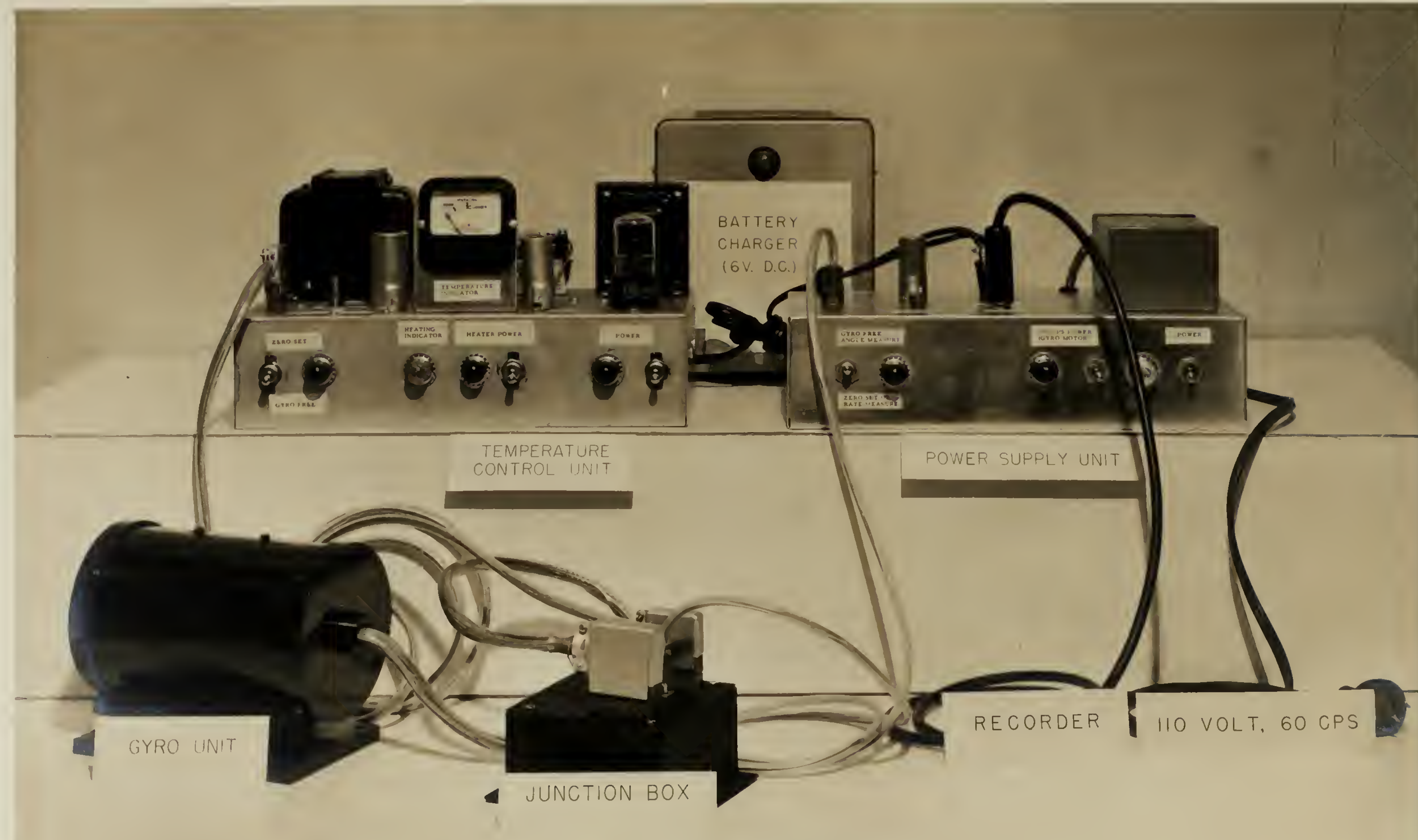


Figure II. System Components.
(Feedback Amplifier not shown.)

available to test or plan extensive uses. The immediate applications were measurements of roll angle and of pitch angle.

Roll angle measurements were an important part of a concurrent thesis by Moriera [14]. One test, at least, involved the recording of roll angle as a prismatic (middle body) model returned upright from an initial roll angle. A typical record is shown in Figure III. The model used for this record was in an arbitrarily ballasted condition giving a roll period of about 0.7 sec (5 divisions per second). This record is not intended to show in a significant way the roll damping, except that quality recordings are quickly available. The second sample shows response of the model to a reflected wave in disturbed water in the tank before the water stilled from an arbitrary disturbance.

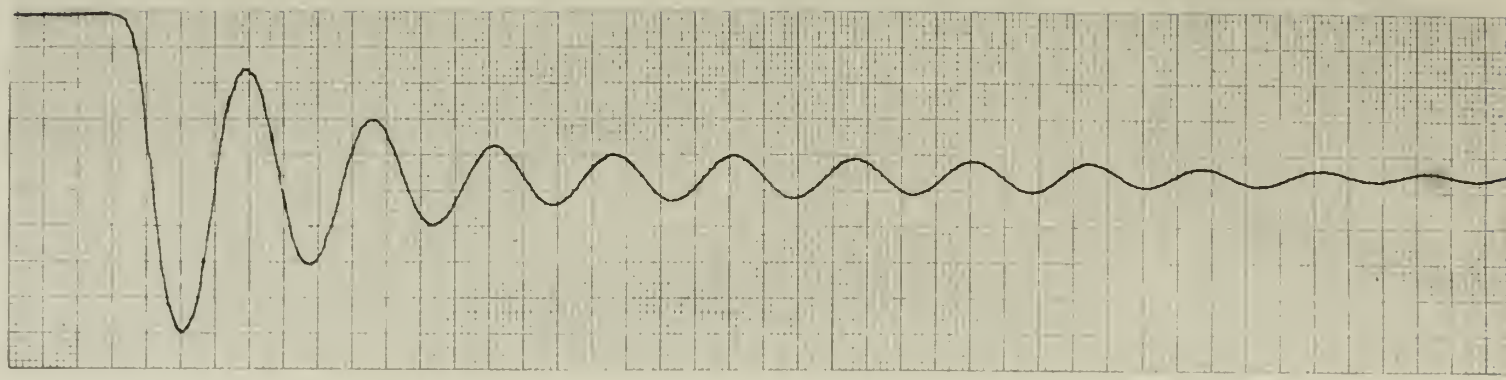
1.4 Outline of the Report.

This chapter has presented a brief introduction to the gyro instrumentation system and its units. For many applications hardly any more familiarity with the system units will be required than is given here and in the recommended operating procedure of Appendix B. Some further confidence may be gained in a more complete understanding of the functioning of the system and purpose of the units. This too will be useful in contemplating extended applications. For these purposes, this report is organized as follows:

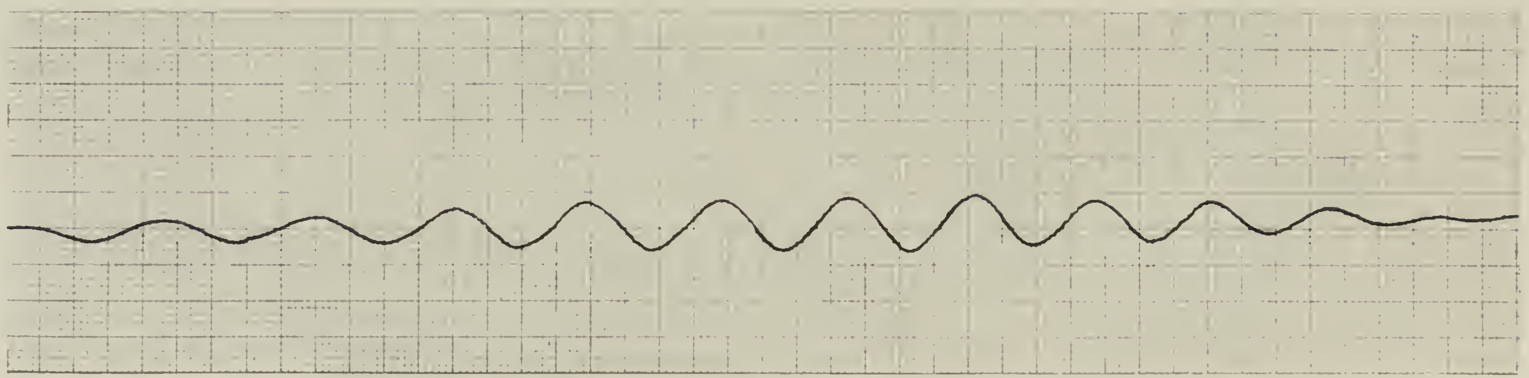
Chapter II. Theory and brief functional descriptions. The details including reference data, circuit and cabling diagrams are all left to the appendices.

Chapter III presents the results that may be anticipated from this system. It should be noted the units in this original form represent in many instances compromises of convenience, flexibility, portability and expense. In several cases these expedients have degraded performance from the ideal that could be realized at some cost. The deficiencies and their price are set forth. This will tend to uncover more potential of the basic system.

Chapter IV presents some views on improving performance and extended uses.



Sample Record. Roll Angle vs time as a "stiff" prismatic body with large GM returns to vertical from an initial roll angle of about five degrees.



Sample Record. Roll Angle vs time as roll increases, then decays, responding to a reflected wave disturbance.

Figure III. Sample Records.

The possible paths of further investigation are included within Chapter IV in two main sections: (1) improvements in the present system, and (2) extending performance to related measurement problems. This writer is not disposed to make single specific recommendations for further development at this time, in the belief that experience with actual measurement problems will illuminate the proper path.

The appendices present additional background information, operating instructions and detailed reference material on the units.

II

THEORY AND DESCRIPTION

2.1 Introduction.

This chapter will present functional descriptions of the system and units. To avoid complications not necessary to an adequate understanding of system operation, details of theory and construction are reserved to the appendices.

2.2 System Theory and Description.

The instrumentation system is shown schematically in Figure I, suitably arranged for pitch angle or pitch angular velocity measurements during a towed-in-waves run. The actual equipment may be identified in Figure II.

The system is built around the capabilities of a type H Integrating Gyroscope (HIG) housed within the Gyro Case. The HIG is a precision instrument known to automatic control and servomechanism designers. It is described more completely in section 2.4 and in Appendix A, which also makes reference to the literature. The remaining units serve the HIG or convert its output to a form acceptable to the recording instrument. The recorder in mind throughout this report will be a Sanborn with type 126 DC Amplifier. Any equivalent equipment with high impedance input and sensitivity of at least 0.5 VDC per degree scale will suffice.

Other than the HIG and the recorder, the remaining units of the system may be dismissed for the time being as simply service units requiring little more than casual surveillance by the operator. The system is initially activated and the gyro brought to temperature. Operation is automatic thereafter. An exception is zero-setting, or returning the gyro to reference position at the start of angular displacement measurements, but this is a matter of a single switch. It is, of course, prudent to de-energize certain circuits such as the vibrator power supply when their use is

not imminent.

Initial installation requirements will not ordinarily be severe. The gyro case weight is about 6-1/4 pounds. The junction box weight is about 1-1/2 pounds. This is within the ten pounds or more ballast required in even a 4 or 5 foot model. The sensitive axis of the gyro is aligned with the gyro case which should not be difficult to mount. Errors would be proportional to the difference between the cosine of the small error angle and 1.000, and therefore small.

The uses of the feedback amplifier should be distinctly differentiated. This unit, (1) may be used to zero-set the gyro when making angular displacement measurements, but an alternative method ("60 CPS caging") is provided which eliminates the necessity of the amplifier for this type measurement. (2) The amplifier is essential and must be used for angular rate measurements, and zero-set or caging is not required in rate measurements.

Dismissing the auxiliary services, the operation of the system is essentially the operation of the HIG, which will be described for angle and rate measurements.

2.21 Angle Measurement.

The HIG is sensitive to angular motion only, and only that component of angular velocity about the sensitive axis. In Figure I the sensitive axis is aligned for pitch motion. The HIG is sensitive to angular velocity but the output of the HIG unit by itself is proportional to input rotation angle. This is not to be confused with other well-known gyro applications - compasses, stable verticals, directional gyros, rate-of-turn indicators, etc. The output of the HIG by itself is the time integral of the input angular velocity; but the integral of the input angular velocity is the input rotation angle. Therefore the output angle of the HIG is directly proportional to the input angle.

The above described property of the HIG by itself is invariant. Auxiliary equipment is sometimes used (a feedback

amplifier) to give overall performance of a different nature. The HIG still operates as above.

The above operation is sufficient for angle measurement and this is the system used. Auxiliary services include temperature control and indication, signal circuits to read the output angle (equal to the input angle), detection prior to recording, etc.

Some method must be provided to center or cage or zero-set the gyro to a reference position at start. Two alternatives are provided. (1) Use the feedback amplifier to zero-set, releasing the gyro at the start of measurement. (2) Use "60 CPS caging", the zero-set switch on the Temperature Control Unit, and the feedback amplifier is not required. In either case the appropriate receptacle in the junction box must be used for the gyro cable when the unit is initially installed but need not be changed thereafter.

Either method of zero-set is equivalent to an electrical centering spring. The 60 CPS caging "spring" is notably less stiff than the equivalent "spring" using zero-set by feedback. In either case the "spring" is not stiff enough to stop all gyro indication. In fact, the gyro will respond with an output signal proportional directly to input rates. Only when the model is subject to zero rates will the centering "spring" return the gyro to zero-rate and zero angle reference position. This situation, far from unfavorable, in fact provides for angular rate measurements as follows.

2.22 Angular Rate Measurements.

The HIG unit itself responds to input rates with an output angle proportional to the time integral of the input rate. This is utilized for angle measurements as in section 2.21. For angular rate measurements a feedback system is used around the gyro. A signal proportional to the output angle is fed back as a torque on the viscous damped gimbal of the gyro. The feedback thus counters the normal precession of the gyro – but the magnitude of this feedback is directly proportional to the input rate. Therefore the feedback signal is detected and used as a direct measurement of angular rate.

In rate measurement the feedback signal keeps the gyro always very near the zero-set position. Deviations from the rest position are, with feedback, proportional to the input rate. In this case therefore the feedback amplifier is required and is left in the connection associated with "zero-set" in the angle measuring system when this zero-set system is used.

It is seen by comparison that in fact zero-setting is simply connecting the gyro for rate measuring, and when there is no rate input, the zero-rate indication is the zero-reference position for angle measurements.

The 60 CPS caging system could in some cases be equivalent to a feedback system and the gyro used for measuring rates. The "spring constant" of this connection is relatively low compared with that of the feedback amplifier. This will mean relative over-damping, increased phase lag and deteriorated response at a relatively low frequency, estimated at about 2.5 to 3 CPS. With the feedback amplifier reliable rate measurements to above 10 CPS are considered effortless.

2.3 Description of Units.

The following sections will provide a short functional description of the units. Details of construction will be found in corresponding sections of Appendix C.

Section	Unit	Appendix
2.31	HIG	C-1
2.32	Gyro Case	C-2
2.33	Junction Box	C-3
2.34	Temperature Control	C-4
2.35	Power Supply	C-5
2.36	Feedback Amplifier	C-6

2.31 HIG Description.

The construction of a very similiar HIG is shown in Figure IV, adapted from reference [10] of this report. Differences are minor and simply due to the HIG on hand being a

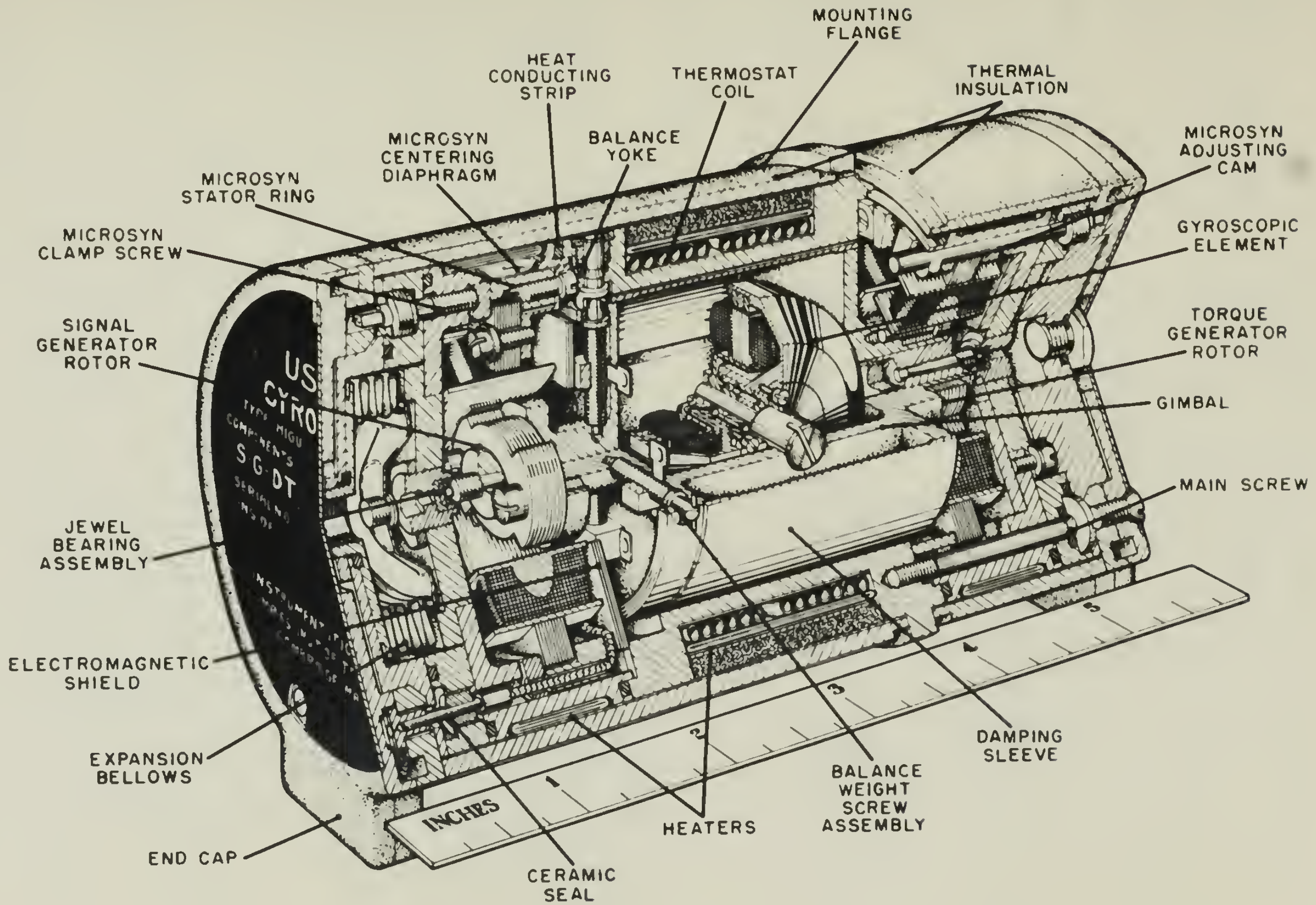


Figure IV. Type H Integrating Gyro (HIG).
(Adapted from reference [10] of this thesis).

production model manufactured by Minneapolis-Honeywell. The gyroscopic element is floated at essentially neutral buoyancy. The flotation fluid is newtonian and provides integration action as described in Appendix A.

The output angle (proportional to the input angle) is "read" by an AC signal from the signal generator. The zero-setting or restoring torques are electrically generated by magnetic action of the torque generator. Connections to these elements – spin motor, signal and torque generators – are brought through the hermetic seal by pins to end caps at both signal generator and torque generator ends. In addition there are electrical connections to the temperature control, indicating, and the heating circuits.

The behavior of these elements of the HIG is described in Appendix A and reference data and wiring diagrams are given in Appendix C.

2.32 Gyro Case.

The Gyro Case rigidly mounts the HIG and provides protection and heat insulation. The HIG is in a cylindrical case which rotates on a bed plate. The sensitive axis of the HIG is fixed relative to the cylindrical case. The rotating feature enables indexing at 3 positions. The case in two positions is shown in the photographs of Figure V. The third is shown in Figure II or Figure VII. The relation of sensitive axis and index positions is also shown schematically in Figure VI.

The electrical leads are terminated in a plug intended for the proper receptacle in the Junction Box. The use of an extension cord between is entirely possible and is provided.

The Gyro Case complete weighs about 6-1/4 pounds and the center of gravity is about 3/8-inch below the geometric center of the cylindrical casing. The case is considered splash-proof but leakage could occur through screw holes during immersion. Gaskets can be fitted to the stuffing box and end caps. The case material is anodized aluminum.

Figure V. Gyro Case.

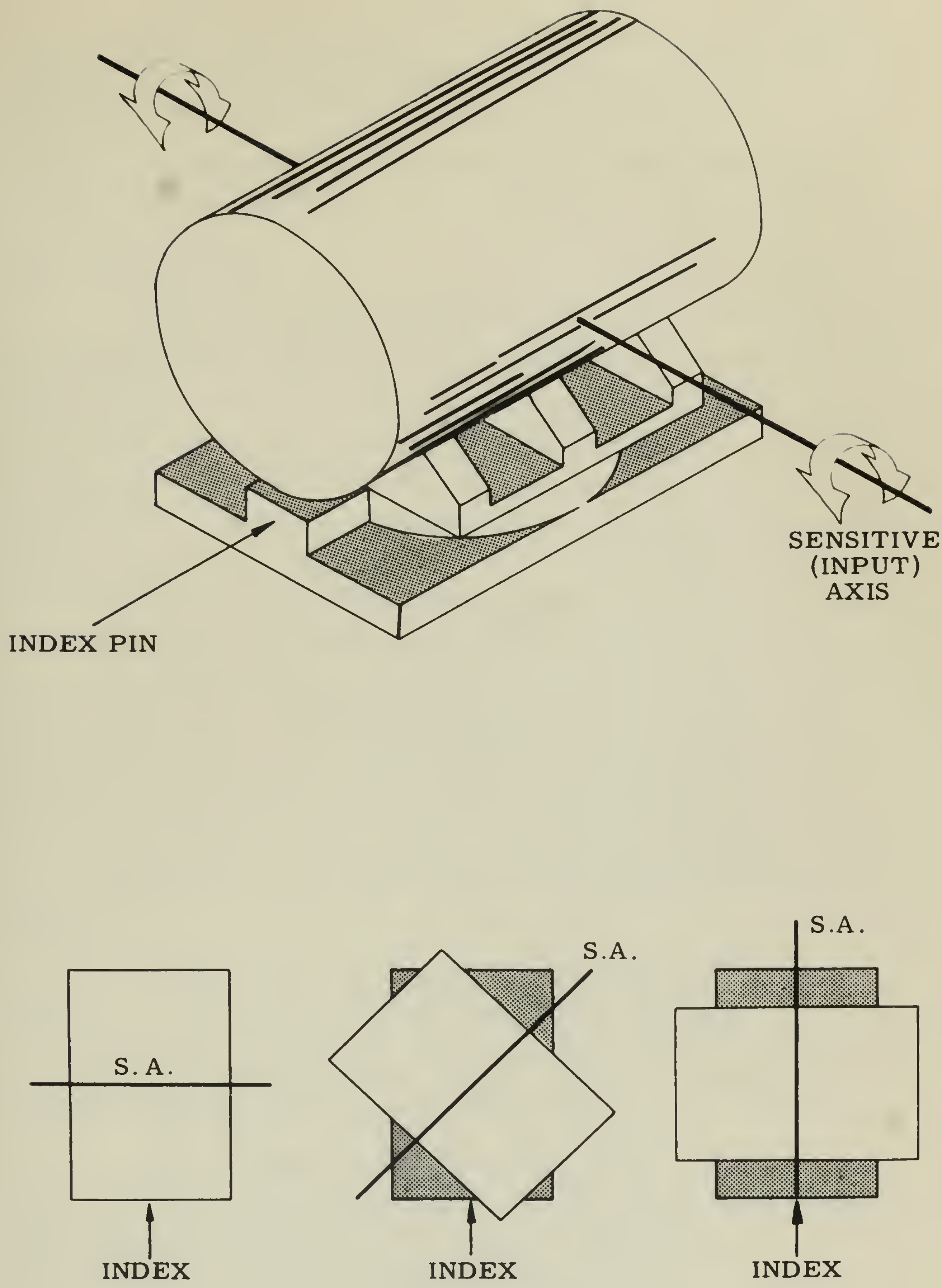


Figure VI. Gyro Case; index positions and Gyro sensitive axis.

The Gyro Case is largely for convenience, protection and insulation; it may be mounted in any position or direction consistent with desired direction of the sensitive axis.

An assembly drawing and location of mounting holes are included in Appendix C-2.

2.33 Junction Box

The many electrical leads from the HIG in the Gyro Unit are connected in various ways in the Junction Box and routed to the proper units. A principal advantage lies in the fact that all leads to the Temperature Control Unit may be broken prior to a short recording run. Thermal insulation in the Gyro Unit will maintain temperature, with power dissipated by the spin motor, etc., sufficiently uniform for most purposes over a one or two minute interval. This reduces the number of leads to a minimum that must be led from the model to other units. Three wires, plus ground return, will suffice when the feedback is not used, or four wires for rate measurement. All these essential leads are cabled to the Power Supply Unit and may be festooned about the towing apparatus for minimum interference. The photograph of Figure VII shows the Junction Box with cables. Here the power supply cable is in a plastic protective sleeve, and is as large as ever should need be.

There are two receptacles on the Junction Box for the Gyro Unit Cable. The receptacles are used as follows:

(1) For angle measurement and 60 CPS caging. The feedback amplifier plays no part in operations.

(2) For angle measurement and zero-set with the feedback amplifier or for rate measurement with the feedback amplifier. The 60 CPS caging is disconnected and the zero-set switch on the Temperature Control Unit is functionless.

A wiring diagram of the Junction Box is given in Appendix C-3.

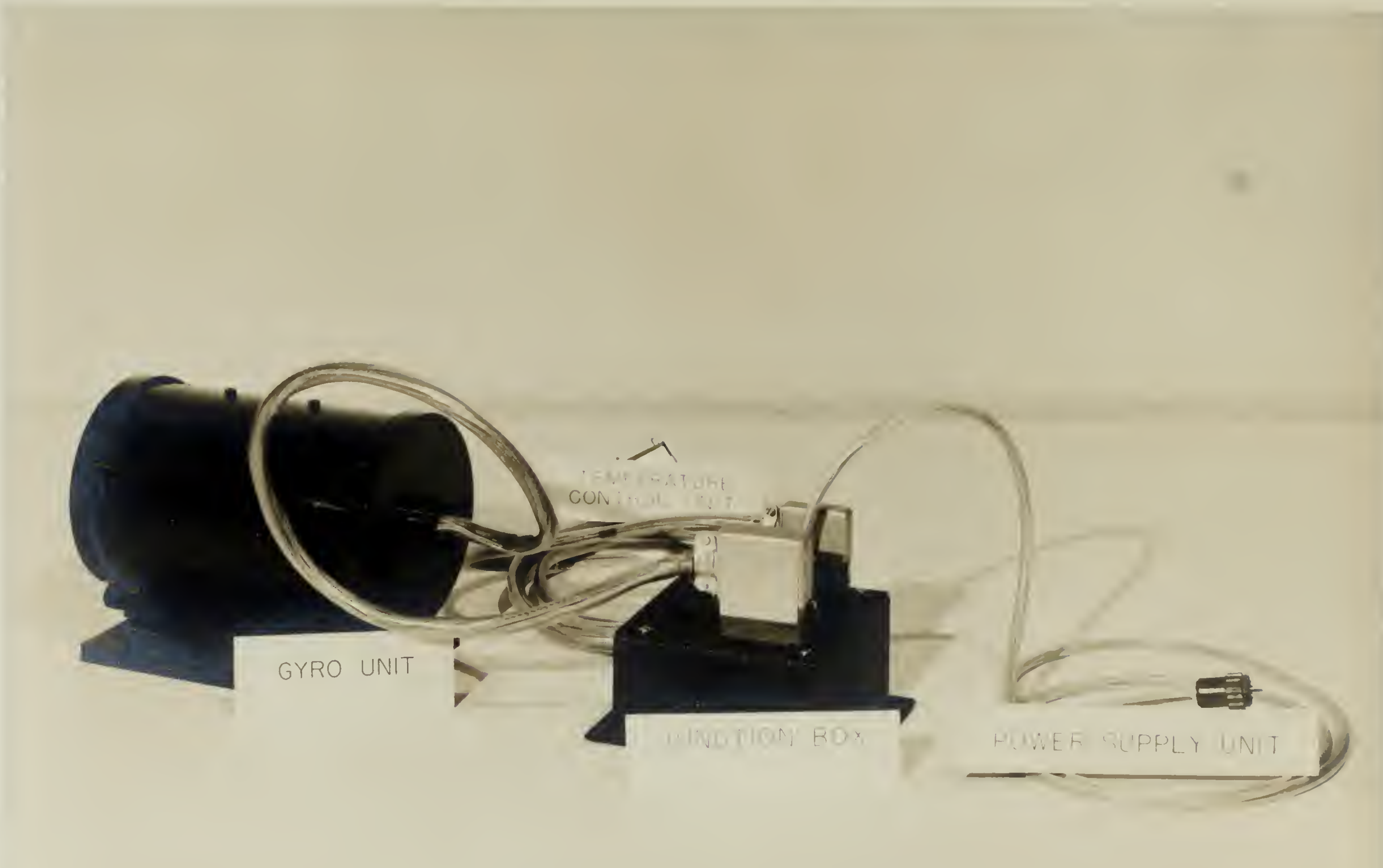


Figure VII. Gyro Case and Junction Box.

2.34 Temperature Control Unit.

Temperature control of the HIG is vital. The viscosity of the suspension fluid is temperature sensitive and this directly affects the gyro sensitivity and dynamic response characteristics. The unit constructed for this control is photographed in Figure VIII. The temperature control circuits require no supervision once "Power" and "Heater Power" are energized. The temperature indicating meter is independent of the control circuits, acting thus as an independent second check on temperature, and is intended only for casual surveillance by the operator.

The 60 CPS zero-set is activated on this unit. The gyro is either free of this circuit or is zero-set by the one switch on.

This unit provides a means for precise temperature measurement which will not ordinarily be required. For this and details of the circuits included, refer to Appendix C-4.

2.35 Power Supply Unit.

The Power Supply Unit (Figure IX) serves for the power functions and is also the location of several vital signal circuits terminating in the jack for the recorder connection.

The gyro spin motor requires a three-phase 400 CPS power supply. Signal circuits can also be served by a 400 CPS carrier. Lacking other sources, this may be obtained from the vibrator power supply in the Power Supply Unit. This supplies a 400 CPS line (one phase is grounded) from which current is drawn as needed at the Power Supply, Junction Box, and Gyro. A source of 6 V.D.C. is required to excite the vibrator. It is prudent to turn off the 400 CPS power when the vibrator is not immediately required. No warm-up time of 400 CPS circuits is required beyond 15 seconds for the spin motor to synchronize.

The chassis of this unit carries the phase sensitive demodulator converting the AC output signal to a DC signal. This circuitry requires no supervision after the recorder is plugged in and the desired recorder deflection direction ("Polarity Reverse") is selected. The output can be tested at a test point provided with a

Figure VIII. Temperature Control Unit.

Figure IX. Power Supply Unit.

high impedance voltmeter, preferably a vacuum tube voltmeter such as Heathkit or RCA Voltohmyst.

The Power Supply Unit is also a convenient location for connection to the feedback amplifier, when it is used.

The feedback amplifier is used as described in the next section, but the only supervision required is correct positioning of the Gyro Free–Zero Set switch on this Power Supply Unit.

2.36 The Feedback Amplifier Unit (FAU).

The Feedback Amplifier is intended to be plugged into the Power Supply Unit whenever the former is used. The feedback amplifier requires no supervision, directly, but control is exercised by the proper switch on the Power Supply Unit as follows:

1. For Rate Measurement. The FAU must be used. The control switch is thrown to "Zero-Set or Rate Measure" and no further operation is required. (The corresponding receptacle in the Junction Box is used on initial installation.)

2. For Zero-Setting by FAU prior to a displacement measurement. The FAU is used. The control switch is set to "Zero Set" for that function until zero is established and is thrown to "Gyro Free" at the start of an angle measurement.

The circuit diagram of this unit is shown in Appendix C-6. The control switch is included in the Power Supply Unit diagram, Appendix C-5.

Figure X. Feedback Amplifier.

III

RESULTS AND DEFICIENCIES

3.1 Performance of the HIG Alone.

The performance which may be expected from the HIG may be inferred from the functional block diagram Figure A-II. Symbols and nominal values of parameters for the HIG-5 are included in Appendix C-1.

Assume the torque generator is used only to establish zero reference, either by 60 CPS zero-set or by feedback amplifier, and that torque generator control current i is zero thereafter. The output voltage e_o is determined by the input angle θ. Neglecting the delay factor, e_o is proportional to θ by the constant $K_{sg}H/B$. Including a factor for the conversion of e_o to a dc voltage, this gain is about 0.5 to 0.6 volts/degree for the system in its present form.

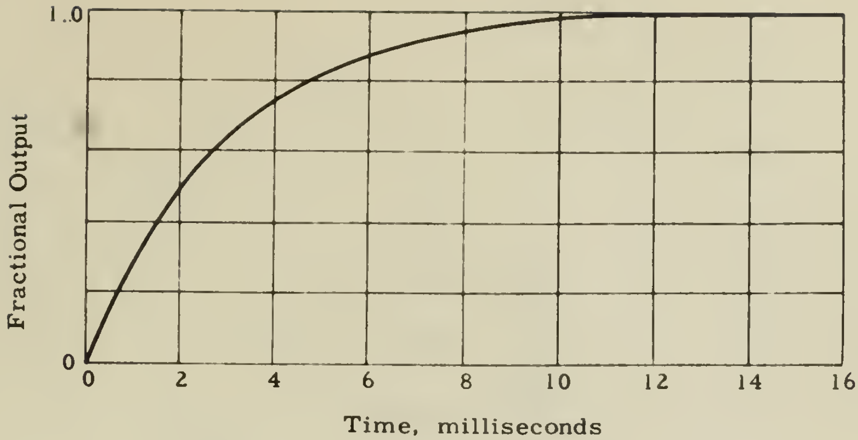
For the present, assume K_{sg}, H and B are constant and consider the normalized response $(e_oB/K_{sg}H)/\theta$, the output per unit input. This is simply the effect of the delay factor $1/(\tau s + 1)$. $\tau = J/B = .00285$.

The normallized gyro output for types of inputs is shown in Figure XI.

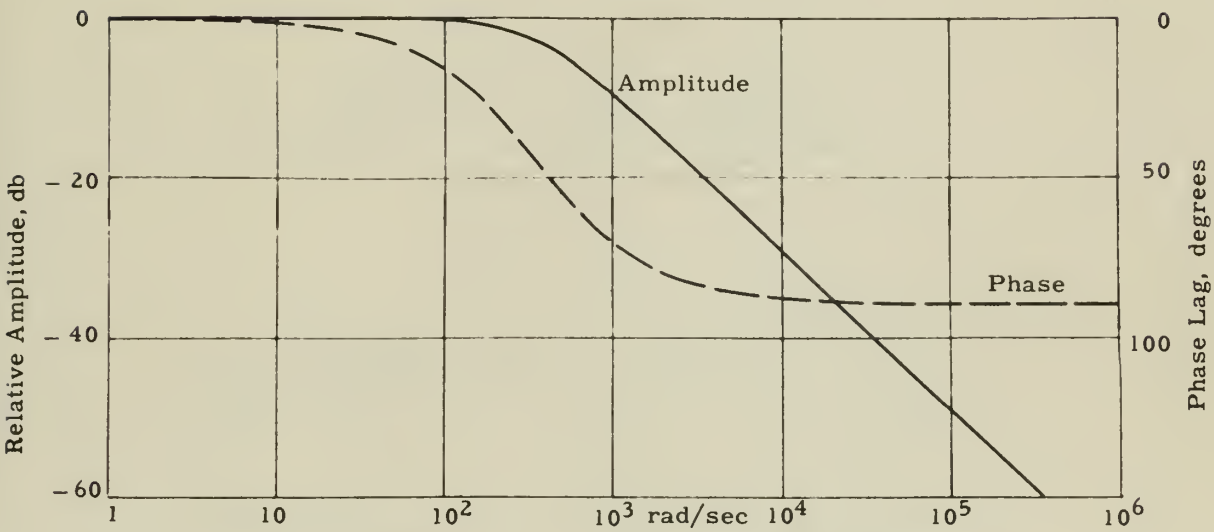
3.2 Performance of the HIG with Feedback.

The HIG with feedback is shown in Figure XII. The analytic description of the HIG remains as in Figure A-II. Symbols are defined in Appendix C-1. The feedback amplifier is assigned a gain $-K_{fb}$ in milliamperes torque generator current per volt to the amplifier from the signal generator. The negative sign infers negative feedback: e_o causes a current i phased to decrease the output angle.

The solution for e_o with feedback shows that at low frequencies e_o is directly proportional to the input angular velocity

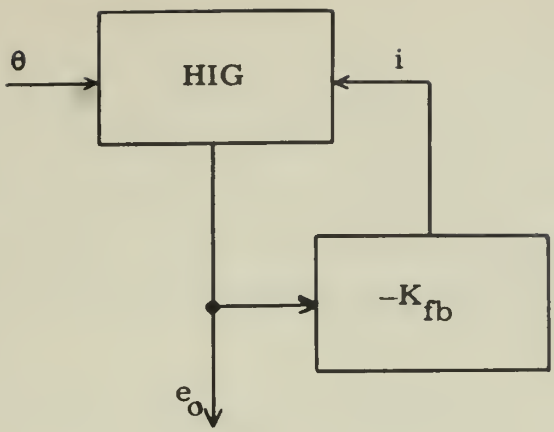


Unit Step Response



Sinusoidal Frequency Response

Figure XI. HIG Output for Unit Step and Sinusoidal Inputs. (Adapted from reference [10] of this thesis).



$$e_o = K_{sg}\,\frac{H/B}{\frac{J}{B}s + 1}\,\theta + K_{sg}K_{tg}\,\frac{1/B}{s(\frac{J}{B}s + 1)}\,i$$

$$= \frac{H/K_{fb}K_{tg}}{\frac{s^2}{\omega_n^2} + \frac{2\zeta}{\omega_n}s + 1}\,(s\theta) \qquad s\theta \sim \dot{\theta}$$

$$\omega_n^2 = \frac{K_{fb}K_{tg}K_{sg}}{J} \qquad \zeta = \frac{B}{2\sqrt{K_{fb}K_{tg}K_{sg}J}}$$

Figure XII. HIG with Feedback.

with the constant $H/K_{fb}K_{tg}$. In this case the HIG plus feedback is acting exactly like a rate gyro, or a spring-restrained gyro, in which the spring constant is determined by the loop gain $K_{fb}K_{tg}K_{sg}$. Increasing loop gain (ie amplifier gain) has the usual advantages and disadvantages in the spring constant in a rate gyro. Increased stiffness (gain) means a higher natural frequency, but decreased sensitivity and less damping (a higher resonant peak). This is illustrated in Figure XIII which shows the natural frequency and damping constant as functions of the loop gain.

3.3 Principal Functional Restrictions.

There are certain requirements – certain ground rules – which must be met in operating the HIG system. Fortunately these are not severe requirements and for many purposes will not be of consequence. Extending performance to higher levels of precision or sensitivity can only be done with these requirements in mind.

3.31 HIG Drift.

Gyro drift will be of no consequence in rate measurements of the type in Section 3.2. Drift will be of consequence in angle measurements by the system of Section 3.1 or in stable-platform systems discussed in the literature.

Consider the gyro system set up for angular measurements. With caging or zero-set switches closed, no change in output will occur. With the gyro set free, the output will gradually increase, indicating an apparent input though none can be detected at the gyro case with respect to fixed coordinates on the earth's surface. This total output from all causes with no apparent input is termed drift for the purposes of this report and includes the following causes:

(1) Output due to earth's rotation. This is strictly an integration of earth's angular velocity component along the HIG sensitive axis in normal HIG fashion. This is not an imperfection and it should be expected in a sensitive instrument such as this

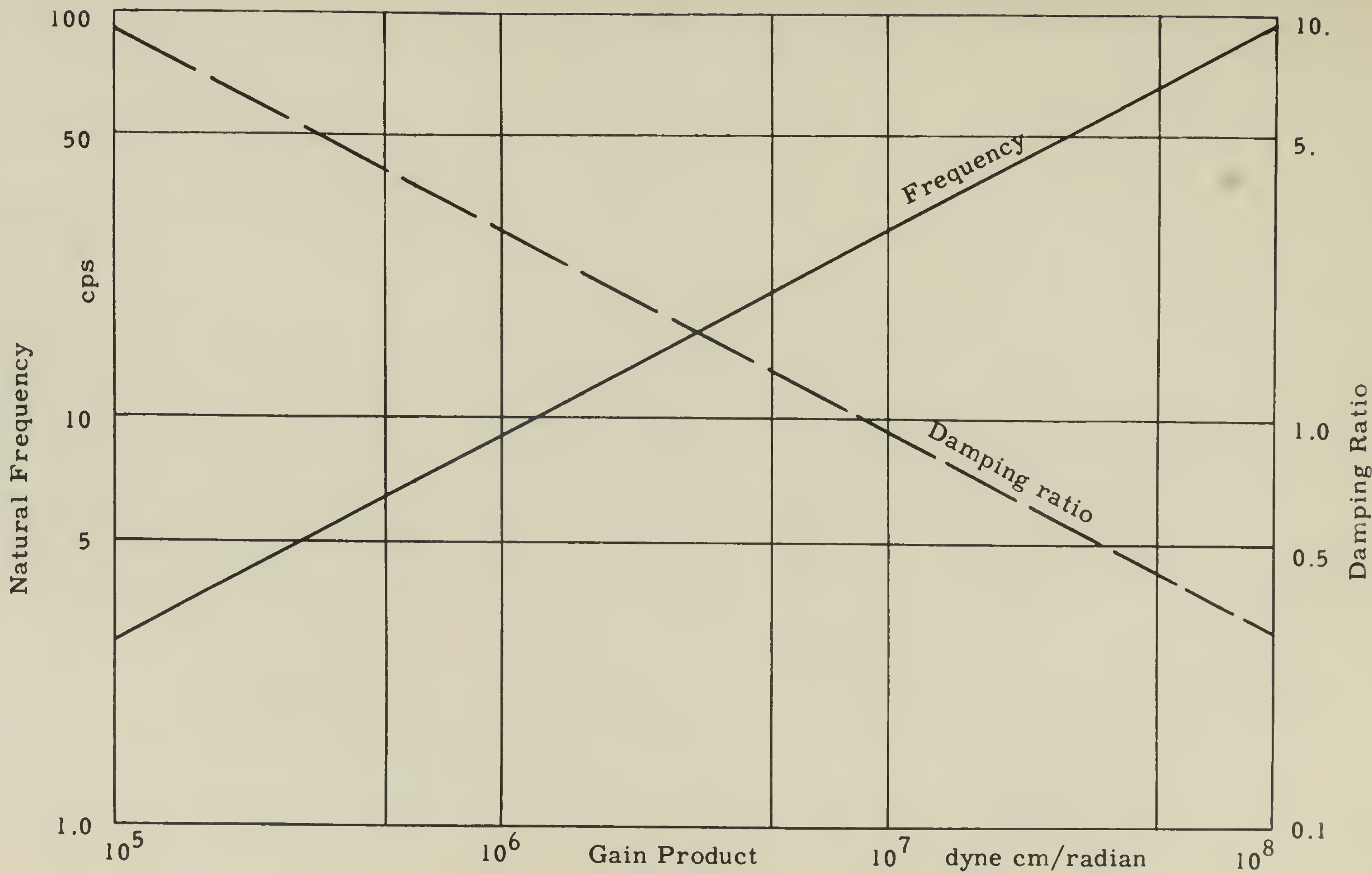


Figure XIII. Natural Frequency and Damping of the Rate System.

referring to a fixed-in-space inertia reference system. The maximum component of earth's rotation is about 15 minutes arc per minute time. This is reduced by any skewness of the earth's and HIG sensitive axes in the usual manner of components. Thus perpendicularity of the sensitive axis to earths axis would reduce this effect to zero – which probably can not be arranged for all model measurements in all towing tanks. For arbitrary orientations of the sensitive axis in the horizontal-to-earth's-surface plane, the earth's rate is reduced by sin θ cos L. Angle θ is that between the sensitive axis and true East – West. Angle L is the latitude angle. The correction is sin L for a vertical sensitive axis.

(2) Mass and Torque unbalance. Any mass unbalance in the gyro element or gimbal will cause an output drift that will vary with gyro orientation in the gravity field. There may also be torque unbalance in the bearings, flexible leads, thermal gradients, etc.

Maximum effect of the earth's rotation corresponds to a gimbal torque of about 7.27 dyne-cm. Additional torques due to mass and torque unbalance may total 10 dyne cm when the gyro is operated in reasonably favorable circumstances and may be as high as 30 dyne cm under less favorable temperature control and torque balancing. The latter figure corresponds to a drift of about 1 degree per minute time.

Drift rates are exceedingly complicated to predict and to control at the lower levels. Without earth's rate components (eg using East-West axis orientation), the drift rate can be made small (15 minutes/minute or less) quite readily by injecting some balancing torque generator current as in the 60 CPS caging connection, or by trimming the pattern field as in the feedback amplifier connection. Attempts to reduce drift to very low levels are not encouraged without further study and attention to:

a. precision of temperature control.
b. regard to power dissipated within the gyro due to spin motor, pattern fields, etc.
c. stability of microsyn and motor currents.
d. methods of torque generator compensation.
e. the feasibility of accepting a slow drift of zero-reference, as it exists, or

f. reanalysis of procedure, permitting a shift to rate measurement.

3.32 Sensitivity Variations.

Sensitivity constants are given in Figures XII and A-II and mentioned in Sections 3.1 and 3.2.

For a given gyro the parameters will depend on temperature and the corresponding pattern winding current and frequency.

Temperature markedly affects sensitivity through the damping coefficient B. Viscosity increases, B becomes larger, and sensitivity decreases as temperature decreases below design. Design temperature is signified by a sensing element resistance of 780 ohms. Temperature dependence is referred to this resistance element, which in turn has a temperature sensitivity of about 1.5 ohm per degree Fahrenheit. The sensitivity temperature coefficient is about 3 per cent per ohm. A sensitivity of 0.5 volts/degree at 780 ohms will thus decrease about 15 millivolts/degree per ohm decrease. (Operation at higher temperature is to be avoided.) This is the factor to bear in mind when contemplating an extended run without temperature control. Two minutes after a heating cycle, the heat loss from this gyro case has been low enough to permit a temperature decrement of less than 1 ohm/minute. Precise initial temperature control prior to disconnect, with perhaps a small current supply to the heaters during a run, should permit control of this decrement to as small a number as desired. Pattern field and spin motor dissipation help to keep the temperature decrement small.

The signal generator sensitivity K_{sg} and the torque generator sensitivity K_{tg} depend on their respective pattern field excitations.

$$K_{sg} = 8.5 \times 10^{-4} \times i \times f \text{ volts/radian}$$

$$K_{tg} = 2.5 \times i \cos \phi \text{ dyne cm/milliamp control current.}$$

i = respective pattern field current.

f = excitation current frequency, cps. (400).

ϕ = phase angle between control and field currents, normally 0° or 180°.

This should make clear the essential nature of stability of pattern field current. This is difficult with a vibrator signal carrier supply.

The sensitivity also depends on H, the spin momentum. This in turn depends on the synchronous spin motor speed. Synchronous speed depends directly on stability of the frequency of the a.c. motor supply.

The stability of the 400 CPS supply from the vibrator is not outstanding. Frequency regulation is 1 per cent or better, but pattern field currents drawn from this source will be subject to random fluctuations about the mean. The vibrator supply is a convenience in the absence of more desirable laboratory or rotating machinery supplies.

The current waveform in torque and signal generator windings is normally expected to contain less than 1 per cent harmonic distortion. This is not possible with the very distorted waveforms of the vibrator supply. Limited vibrator voltage and high field impedance make filtering difficult.

3.33 Limitation by mechanical stops.

The gimbal axis is provided mechanical stops at about ± 6 degrees. The signal generator microsyn is non-linear at the extreme range. This clearly limits angular measurements to small angles, when the output angle per input angle sensitivity is H/B, nominally unity. There is some hope for measuring larger angles by decreasing sensitivity H/B by operating at lower than design temperature. Sensitivity is reduced about 50 per cent by operating about 16. ohms below design level of 780 ohms. This doubles the allowed input rotation. At some low temperature the suspension fluid will become non-newtonian, in fact it will freeze solid at room temperature. The area of operation at temperatures more than a few ohms low is one deserving more study. Low temperature has adverse dynamic response influence.

Sensitivity can be decreased by sacrificing spin momentum H. This could be done by decreasing supply frequency

below 400 CPS, it is believed. This will decrease gyroscopic torque and permit greater input rotation prior to output limitation. The manufacturer's opinion on this is not now known.

The apparent sensitivity can be altered by using feedback principles. This is recommended for further study, if needs warrant this extension.

3.34 Temperature Dependence of Dynamic Response.

The time constant of the delay factor is adversely affected by decrease in temperature, or increase in viscosity. As the time constant increases (lower temperature) the higher frequency response deteriorates. The phase lag increases. The time constant increases about 3 per cent per ohm decrease in sensing resistance. The time constant is nominally 0.00285 seconds, corresponding to a break frequency of about 51 CPS. This normally gives some latitude in angle measurements by the system of Section 3.1.

The increased phase lag due to low temperature will be a complication in closed-loop systems discussed in the literature. Ideally the phase lag can be overcome in the rate measurement-system of Section 3.2, but the added lag will probably emphasize other circuit time constants.

IV

IMPROVING AND EXTENDING PERFORMANCE

4.1 Improvement of the Present System.

It should be made clear the form of the present system is a compromise of simplicity, flexibility, portability, expense, and time allotted this investigation. Improvement can be suggested along the following lines.

4.11 The 400 CPS Supply.

Output of the vibrator used is subject to fluctuation and has very high harmonic content. Driving the vibrator from a 6 V. battery charger without a battery "floating on the line" also modulates the 400 CPS with 60 CPS ripple. The signal sources, including pattern field excitations, should be constant and of pure waveform. The signal circuits could use other than 400 CPS frequencies. Signal generator sensitivity will be affected. Either a laboratory source with power amplifiers delivering the excitation current or an alternator are recommended.

The spin motor requires three-phase 400 CPS. Gyro performance is less sensitive to small changes or harmonic content in this source.

Aircraft inverters or alternators for three-phase 400 CPS power are readily available, sometimes including government surplus. Use of such a source will have advantages at the expense of simplicity and portability.

4.12 Heater Supply.

The HIG heaters are intended for 28V. D.C. The 150 watt heater is not recommended by this writer for use without current limiting. Maximum heater circuit power is 225 watts. In the absence of a D.C. source, a 24V. A.C. source is available. The disadvantage of this technique is less precise temperature regulation. The temperature control operates on a 60 CPS carrier

system. The 60 CPS heater windings induce parasitic voltages into the sensing circuit. This confuses the phasing of the control circuit for reliable operation and maximum sensitivity. Removing the heater circuit A.C. connection jumper and connecting a D.C. source should enable phasing of the control circuit to reliable control over a sensing element resistance change of less than one ohm. This sensitivity was achieved by this basic control circuit operating without heater current influence, and is considered to be well within range of current techniques.

4.13 Constant Calibration.

(a) Angular Measurements.

When the gyro sensitivity is constant a constant calibration constant and comparison voltage can be established. This will enable connection of a recorder and instant gain adjustment for scale deflection corresponding to gyro sensitivity. This will require an improved signal circuit source and elimination of parasitic couplings in the heater circuit – control circuit, and experience in knowing what sensitivity is required.

(b) Rate Measurement.

Stability of the gyro sensitivity will enable constant rate calibration, providing the feedback amplifier gain is stabilized. This can be done in the manner of analogue computer resistive-feedback "computing amplifiers." Their gain is the ratio of two precision resistors, readily determined to within less than one per cent.

4.14 Improved Circuitry.

In addition to the above, the circuitry of the present system can be reviewed and, in time, improved.

(a) The pattern field excitations, coming from high impedance, stable sources of good waveform, can be fixed at desired levels without the need of such expedients as resonating networks in the torque field. Purity of waveform will eliminate the necessity of resonating the signal generator secondary.

(b) Improved signal circuit waveform and stability and precision of temperature control will make worthwhile improved drift-compensation.

(c) The mechanical need demodulator can be replaced by an everlasting phase sensitive demodulator such as the Schriner circuit.

(d) Use of a direct-current heater circuit source will enable improved temperature regulation precision.

4.2 Extending Performance.

A fascinating feature of the HIG instrumentation system is its potential for further development. Obvious extensions might include the following:

1. Enable acceleration measurements, affording the opportunity to select a time record of angle, rate, or acceleration. Acceleration is likely to be a very desirable derivative because of its intimate relation to slamming and strength studies.
2. A method of extending the range of angle measurement beyond six degrees without decreasing operating temperature and compromising dynamic performance.
3. The simultaneous presentation of two or three parameters, say displacement and velocity, for use in phase-plane presentations. Very likely the future will see non-linear treatments of ship motions, perhaps including the phase-plane technique. The HIG system can be extended to simultaneous measurements for these presentations.
4. Packing for portability, for very convenient field testing. The present subdivision into many units is rather arbitrary and to promote further development by alterations in any one or two logical units. For improved portability, no doubt the physical arrangement can be markedly improved.

4.21 Extending Performance by Operational Feedback.

Appendix A-4, Figure A-II, derived the transfer function for the HIG alone. Section 3.2, Figure XII, derived the transfer function for the HIG with pure gain feedback, $-K_{fb}$. Interesting possibilities unfold if the feedback is considered to be operational

instead of pure gain. Define the feedback function to be $-KG)_{fb}$ where $G = G(s)$, an operational gain, and K is the sensitivity constant.

The closed-loop solution, since $i = -(KG)_{fb} e_o$, is

$$e_o = \frac{K_{sg}\, H/J}{s^2 + \frac{B}{J} s + \frac{K_{sg} K_{tg} K_{fb}}{J} G_{fb}} \, (s\theta).$$

For the pure gain case, $G_{fb} = 1.$ and the rate-measuring system results. If one could obtain derivative feedback, $G(s) = s$, the output voltage becomes proportional to angle θ and the angular sensitivity may be controlled by the feedback loop gain. If by suitable switching, integral feedback were available, $G(s) = 1/s$, then the output would at low frequencies be a measure of angular acceleration. The closed loop in the latter case is unstable and stabilization means must first be found. Providing the circuit details could be developed, the system would thus enable, by simple feedback-characteristic switching, a direct measurement of angular displacement, velocity or acceleration.

An additional advantage accrues from the availability of the electrical equipment above. That is the availability of signals proportional to several parameters. For example when using derivative feedback, the output e_o is proportional to angle, but simultaneously the torque generator current is proportional rate. Thus signals are available from the one system for position-velocity "phase-plane" studies. A similar condition exists with integral feedback. Of course the operational amplifiers can also be used open – loop to perform their operation if they are separate units. A compact and less expensive system might simply select the operation mode desired by switching the feedback element of a single computer-type operational amplifier.

It must unfortunately be recalled the data signal system of the HIG is of the suppressed-carrier type. Known high-performance operational amplifiers generally are for so-called D.C. data

systems, and their use would possibly imply demodulation prior to, and remodulation after, operations. Since the data frequencies are low there might be hope for simple equipment. The matter is certainly believed to warrant further investigation.

4.22 Extending Performance by Rate Gyro.

The output range limitation (Section 3.33) will no doubt be an annoyance in some applications. Increasing the apparent range (decreasing the sensitivity) by operating at a low temperature or with reduced spin-momentum may not be acceptable (Section 3.34). The preceding section suggests operational feedback, but this will require some feasibility study for derivative feedback may be difficult to realize and noisy. Another attack would be rate feedback direct from the motion input by a rate-gyro. This scheme will also make simultaneous rate and displacement measurements.

The rate-gyro (such as a Doelcam K-31) is visuallized mounted on the moving body with its sensitive axis paralleling that of the HIG. The output of the rate gyro is delivered through a current amplifier to the HIG torque generator in a negative sense; ie, the rate signal tends to develope a torque opposing the M_{ge} torque (Figure A-II). Clearly, a proper rate gyro gain could keep the net HIG gimbal torque zero. The net gimbal torque would be $(H - K_r K_{tg})(s\theta)$ where K_r is the rate gyro gain. The overall transfer function becomes

$$e_o = \frac{K_{sg}}{B} \frac{(H - K_r K_{tg})}{(\frac{J}{B} s + 1)} \theta ,$$

to be compared with Figure A-II. Adjusting the $K_r K_{tg}$ gain clearly controls the sensitivity without abnormal temperature or deterioration of dynamic characteristics. This scheme is believed to be straightforward, providing a rate-gyro is available.

APPENDICES

APPENDIX A

SUPPLEMENTARY INTRODUCTION TO MODEL SEAWORTHINESS TESTING AND INSTRUMENTATION

A-1. The following supplementary information is intended to serve as background in three areas of interest relative to this investigation.

Section A-2. The general area of ship motions and seaworthiness.

Section A-3. The M.I.T. Towing Tank and seaworthiness testing.

Section A-4. The Type H Integrating Gyroscope (HIG) and its applications.

A-2. Technical Interest.

The general area of technical interest in seaworthiness and ship motions is indicated in a number of well-regarded references. Introductory to these might well be a recommended standard nomenclature. This is presented in reference [1] which also reports in handbook style recommended definitions of axes and angular motions. Unfortunately, the authors of the following references have in many instances found it necessary to deviate from the recommendations.

The approach to which this writer subscribes is approximately described in reference [2]. Herein the authors present a unified analytic concept for describing and analysing the complex sea motion and the ship response operators to yield ship motion predictions. It is to the merit of this reference that it includes the ability to treat complex motion in the irregular seaway, but it is clearly not limited to this. For present purposes attention may be focussed on the analytic characterization of the vessel by "response amplitude operators."

It is known response operators may be obtained experimentally

or approximately by analytic techniques. In addition to that previously cited, references [3] and [4] are concerned at length with such operators. A casual acquaintance with these references will readily introduce the reader to the interest in obtaining experimental data on observed motion and from which response operator information may be deduced when the input wave motion is also known.

The response operators, or dynamic coefficients, have been more fully investigated for motion in the horizontal plane for their direct bearing on the stability and ability of steering and course-keeping. We do not visualize immediate application of our system to this effort, being more concerned with pitch and roll than with yaw. The system is, however, directly adaptable to this situation and for completeness we mention typical pertinent references for horizontal-plane applications. These references [5] and [6] do not name response operators as such. Treatment of the subject matter of these latter references with the techniques of the former references will repeat the results of the latter and prove instructive examples in application of the principles of the former.

As made clear in [5] and [6], surface vessel motion in the horizontal plane may be dynamically unstable. The possibility of instability in the vertical plane exists for submarines. This is discussed in reference [7].

The preceding references have stressed interest in improved analytic understanding and technique. Very real and direct interest in rough weather testing is graphically illustrated in reference [8]. Here is shown speed reduction and pitch angle for various sea wave lengths. Also shown is predicted vertical acceleration at the bow. This relates directly to strength studies. Rough weather or seaworthiness tests such as this are within the capabilities of the M.I.T. Towing Tank.

A-3. The M.I.T. Towing Tank and Seaworthiness Testing.

The previously cited references describe generally the value and methods of obtaining ship response operators and of conducting seaworthiness tests. Such tests are within the capabilities of the M.I.T. Towing Tank and have been conducted for some time.

The M.I.T. Towing Tank is described in reference [9]. This reference can be supplemented, for instance, by an increasing number of theses at M.I.T. relating to the library title "ships: model testing."

Not all experimental procedures in the previously cited references have been employed in this relatively new facility. Creditable work has certainly been done, of which we mention several recent titles of interest. Paulling in reference [15] applied the stroboscopic-photography technique to measurement of pitch angle. In reference [16] the authors utilize a flashing-light method of photography and from recorded position extract velocity and acceleration in the pitching plane. The method of [15] was applied, for example, in reference [17] during the seaworthiness evaluation of a standard model. Model performance in roll has been investigated at M.I.T. as in reference [18]. As mentioned elsewhere a concurrent thesis, [14], required roll measurements and utilized the gyro system of this report.

A-4. The Type H Integrating Gyro.

This system of angular motion instrumentation is based on the performance of a floating integrating gyro. The floating integrating gyro is one of a series called Type H Units developed by the Instrumentation Laboratory at M.I.T. This unit is referred to as the "Type H Integrating Gyro" or HIG Unit. The type H series, including the HIG, is described in an Instrumentation Laboratory Report [10]. A less detailed application of the HIG is reported in reference [11]. Additional description of an HIG Unit is given in reference [12] which also discusses relatively advanced type applications for which this instrument was designed. The basic design features of these instruments have been translated into production items by several manufacturers, including the Minneapolis-Honeywell Regulator Company. Their line is described in a number of their own publications, references [13].

The HIG is illustrated in pictorial schematic in Figure A-I. Construction details of a similar unit are shown in Figure IV. Figures IV and A-I are both adapted from reference [10]. The following discussion will lead to the functional diagram of Figure A-II. The gyroscopic element is the rotor of a three-phase 400 cps hysterisis motor.

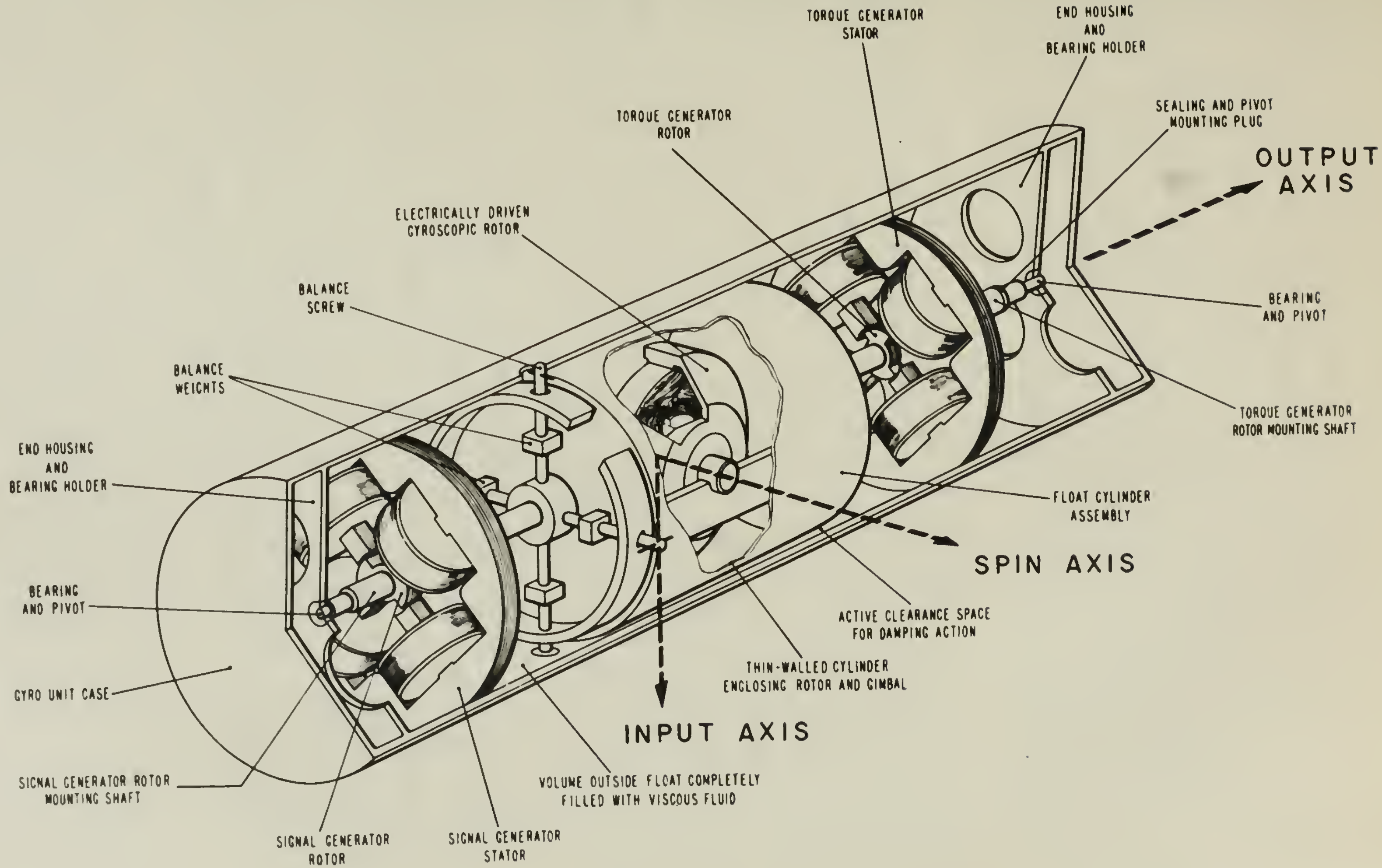


Figure A-I. Pictorial Schematic of the HIG.
(Adapted from reference [10] of this thesis).

The spin axis of the rotor is at right angles to the axis of rotation of the gimbal (the output axis). The gyroscopic element is sensitive to angular velocity inputs about the sensitive axis. The output of gyroscopic element is a torque applied to the gimbal. The magnitude of this torque is the product of the input angular velocity and the angular momentum of the gyroscopic element. The angular momentum of the unit on hand is nominally 10^5 dyne-cm-sec, hence it is sometimes described as an HIG-5. Units of 10^3, 10^4, 10^5, and 10^6 spin momentum are available.

The gyroscopic element and gimbal is enclosed within a thin-walled cylinder float. The gyroscopic element out torque is applied through the box-frame gimbal to this float. The mass of the cylinder and the elements within it is related with the cylinder volume so that the cylinder floats in the enveloping fluid with substantially neutral bouyancy. The buoyant support ensures virtually no weight is supported by the external pivots of the float. There is thus correspondingly small friction torque. The pivots are virtually unaffected by shock or vibration, which forces are transmitted almost entirely through the supporting fluid.

A clearance volume is provided between the float and shell of the unit. This volume contains supporting fluid. The fluid is known to be Newtonian in viscous behavior. The clearance volume and fluid thus provide predictable viscous damping, providing the fluid temperature is accurately controlled. At room temperature the supporting fluid solidifies to a waxy solid and the cylinder float is "frozen" in a solid support. Temperature regulation is provided as is discussed elsewhere.

The output torque of the gyroscopic element is applied to the cylinder float. The torque is opposed by the viscous shear torque of the damping fluid. This is proportional to the cylinder angular velocity, i.e., the angular velocity of the output axis. Thus the output axis angular velocity of the floated gyro is directly proportional to the input angular velocity referred to the sensitive axis. It follows the angle of the gimbal (output axis) is at every instant proportional to the angular displacement of the case about the input axis

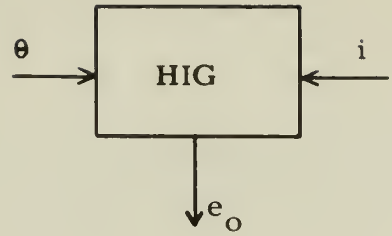
with respect to inertia reference space. The output axis angle with respect to the case is the time integral of gyro input axis angular velocity. For the immediate purposes of this utilization, the output angle is thus a direct measurement of the input angle. It is to be noted this gyroscopic element-viscous fluid configuration provides vastly different information from spring restrained gyros.

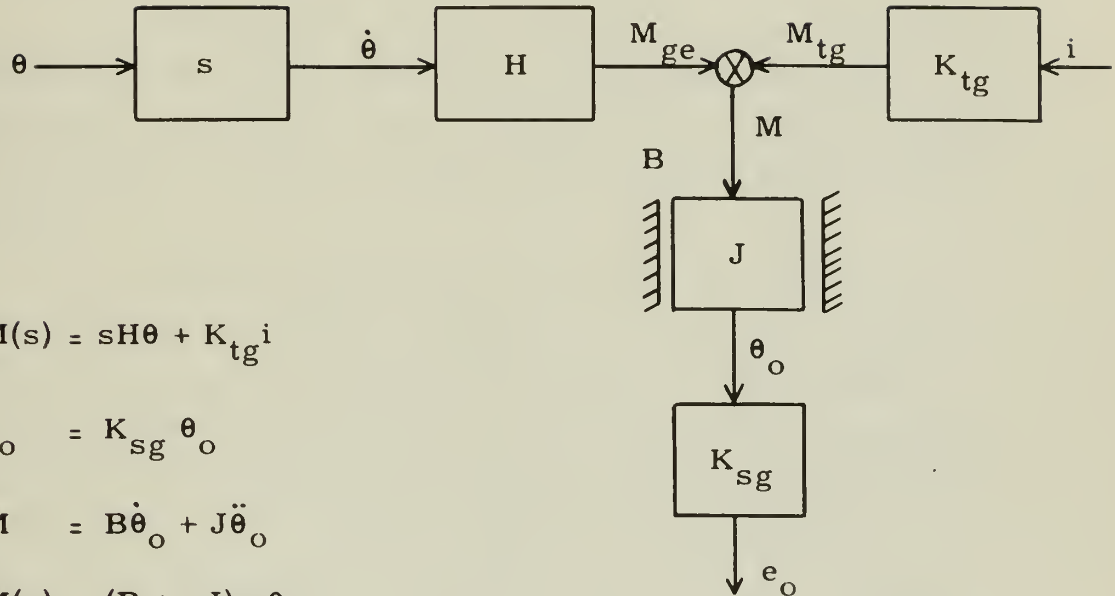
The output axis (float axis) also carries the rotor elements of a microsyn torque generator and a microsyn signal generator.

The microsyn signal generator pattern winding is excited by a reference a.c. excitation. The signal generator output winding produces an output signal voltage by induction from the pattern field. The output signal voltage phase with respect to excitation is determined by the plus-or-minus sense of rotation from zero-set. The magnitude of the output voltage is proportional to the magnitude of the output axis angular displacement. This output voltage from the signal generator thus provides the essential information available from the HIG: an a.c. signal proportional to angle and with phase reversal for opposite angular sense.

The torque generator provides a means of applying an external torque to the float cylinder (output axis). The torque generator may be used to zero-set the output axis to the reference null position. This is referred to as "caging." Zero-set or caging is essential as an initial condition for displacement measurements.

The operation of the type HIG Unit is shown in the functional diagram, Figure A-II. Zero-set initial conditions may be assumed. Symbols and typical values are listed in Appendix C-1, Reference Data on the HIG-5.





$$M(s) = sH\theta + K_{tg}i$$

$$e_o = K_{sg}\,\theta_o$$

$$M = B\dot{\theta}_o + J\ddot{\theta}_o$$

$$M(s) = (B + sJ)\,s\theta_o$$

$$e_o = K_{sg}\,\frac{H/B}{\frac{J}{B}s + 1}\,\theta + K_{sg}K_{tg}\,\frac{1/B}{s(\frac{J}{B}s + 1)}\,i$$

Figure A-II. Functional Diagram of the HIG.

APPENDIX B

DETAILS OF PROCEDURE

B-1. The following procedure is recommended for using the HIG for measurement of angular motion, for example, roll or pitch. (See Figures I and II.)

A. Installation and Interconnection.

1. Mount the Gyro Unit in model with bed-plate fore-and-aft or athwartship. The bed-plate may rest in the model bilge or the case may be inverted and the plate hung from athwartship brackets. The latter will lower the center of gravity of the case unit.

2. With the Gyro Unit mounted, the gyro case is indexed to the proper position relative to the bed plate. The gyro sensitive axis is parallel to the bed plate and is along a short (four inch) diameter of the case, (Figure VI) The gyro responds to input rate components resolved along the sensitive axis in the usual right-hand-rule manner of angular velocity vectors.

3. The gyro lead is plugged into the proper socket in the junction box. The junction box may be mounted in any position in the model, or it may be electrically connected by an extension cord and mounted ashore.

4. The junction box is electrically connected by furnished cables to the following components:

a. The Gyro Unit as in (3) above.
b. The Power Supply Unit.
c. The Temperature Control Unit.

The connections (a) and (b) must be maintained at all times the system is in operation. The connection (c) may be broken immediately preceding a recording run. For a short period, the gyro temperature will be maintained by the thermal insulation in its case. This procedure may be followed when it is desirable to limit

the wiring cables to the model. (Break connection (c) <u>after</u> a heating c cycle.)

5. The Temperature Control Unit is connected to the following:

a. The Junction Box as in 4(b) above.

b. A source of 110 volt 60 cps power. (Convenience outlets are available at the rear of the Power Supply Unit; any other will also serve.)

6. The Power Supply Unit is connected to the following:

a. The Junction Box as in 4(b).

b. A source of 110 volt 60 cps power, but only when the convenience outlets at the rear of the chassis are used. The Power Supply Unit itself does not require 110 volt 60 cps power.

c. A source of 6 volts DC. A battery charger is provided. The battery charger would normally be powered from a convenience plug at the rear of the Power Supply Unit.

d. A recorder such as the Sanborn Recording Equipment with Type 126 amplifier normally available at the M.I.T. Towing Tank. The recorder may also be powered from the Power Supply Unit convenience outlets.

e. The feedback amplifier if this method of zero-set is used.

B. Operation.

1. The "Power" switch on the Power Supply Unit is turned on. The Temperature Control Unit switches for "Power" (green pilot) and "Heater Power", (green pilot) are turned on. The gyro Heating Indicator (yellow pilot) should go on, and the temperature meter should read approximately room temperature if the gyro unit is cool. The gyro is now heating. The heating process may take up to 20 minutes. Approximately one-half hour is a recommended minimum for temperature stabilization. The system will be operable as soon as the gyro reaches operating temperature.

2. When the gyro is at or near operating temperature, the

spin motor may be energized by the "400 CPS Power - (Spin Motor)" switch (green pilot) on the Power Supply Unit. The spin motor comes to operating speed very quickly. It is recommended the 400 CPS power be de-energized during any extended non-operating periods to save wear of the 400 cycle vibrators.

3. The gyro is zero-set (caged) by the "Zero-Set" switch (red pilot) on the Temperature Control Unit for 60 cycle caging, or by using the feedback amplifier and the zero-set switch on the Power Supply Unit.

4. The recording system (Sanborn) is made ready by energizing "Power" and centering the pen.

5. Readiness for operation is indicated by:

a. Temperature Indicator reads in the operating zone.

b. The Heating Indicator (yellow) light goes on and off, indicating control by the Temperature Control Unit.

c. The spin motor has been allowed 15 seconds to reach operating speed and 5 seconds to come to zero-set.

d. There is negligible residual voltage out of the measurement system to the recording amplifier when the gyro is zero-set.

6. To check operation, the gyro may be made free (uncaged, turn off zero-set switch, red pilot, on Temperature Control Unit) and the model given a known angular displacement. The system output will be approximately 0.6 volts/degree. The gain control of the recording amplifier may then be adjusted to give the desired recorder deflection per degree of model motion.

7. Following calibration, the gyro is zero-set and the model allowed to come to the desired initial condition. With the model at rest and the gyro zero-set, zero reference is established. The recording system zero-set (pen centering) may be set as desired.

8. With calibration and zero-reference established, with the spin motor energized and the gyro at operating temperature, the procedure of the particular test underway may be employed. The gyro

is kept at zero-set as long as the model is at zero and is released whenever the model is to be disturbed from zero reference. The interval between release from zero-set and start of recording run should be as short as possible to avoid the ill effects of gyro drift or earth's rotation.

B-2. The following procedure is recommended for use in rate measurements.

A. Installation. Follow same procedure as above except use of the Feedback Amplifier Unit is required. The feedback switch on the Power Supply Unit is left in the rate-measure position.

B. Operation. Operation procedure is the same as above except that the feedback loop is closed. Rate calibration can be accomplished in a model of known period by noting the velocity associated with return to upright from a given displacement angle, or by mounting the gyro on a pendulous platform.

APPENDIX C

REFERENCE DATA ON MAJOR COMPONENTS

C-1. The HIG. Symbols, nominal parameter values, wiring diagram and data.

C-2. Gyro Case.

C-3. Junction Box.

C-4. Temperature Control Unit.

C-5. Power Supply Unit.

C-6. Feedback Amplifier Unit.

THE HIG

Symbols:

B	Viscous damping coefficient due to suspension fluid. Nominally 10^5 dyne cm/rad/sec.
H	Spin momentum, equal to wheel inertia times wheel speed. Nominally 10^5 gm-cm-sec.
i	Torque generator control field current.
J	Gimbal inertia. Nominally 285 gm cm^2.
K_{sg}	Gain or sensitivity constant of the signal generator. See section 3.32.
K_{tg}	Gain or sensitivity constant of the torque generator. See section 3.32.
M	Total external torque applied to the gimbal by the gyroscopic element and the torque generator. Opposed by inertia reaction and viscous damping.
M_{ge}	Torque on gimbal due to action of gyroscopic element, equal to H times the input angular velocity.
M_{tg}	Torque on the gimbal due to action of the torque generator; the product of K_{tg} and control current.
s	Laplace transform operator.
θ	Input angular rotation which is significant because of its corresponding angular velocity, $\dot{\theta}$, about the sensitive axis of the HIG.
θ_o	Gimbal output angle from zero reference.

<u>HIG Data:</u>

Manufacturer:	Aeronautical Division, Minneapolis-Honeywell Regulator Company.
Type:	GG1C-1.
Serial:	1205.

Ambient temperature: −65°F to + 165°F.

Acceleration and vibration test: 50G shock and 30G at 55 cps.

Spin motor: 400 cps, three phase, 12,000 rpm.
11 volts line-to-line to start.
5 watts per phase to start, max.
4 watts typical, 8 volt-amperes.
15 seconds to synchronize.
8 volts line-to-line required to run.
.75 watts per phase to run, max.
.50 watts typical, 1.4 volt-amperes.
Positive wheel rotation is phase sequence ABC to pins 4-G-9.
Positive precession: with positive wheel rotation and input axis vertical with case notch up, the gyro responds to earths rotation with a positive precession, gimbal axis CCW when viewed from signal generator end.

Temperature: Normal operating temperature is 165°F. The operating temperature is correct when the temperature sensing element resistance is 780 ohms. This element is normally connected in one arm of a resistance bridge used in a temperature control unit.

An additional temperature-sensitive resistance element (Victory Engineering Corp. type 32A12) has been attached to the clamp ring of this gyro by a copper terminal. This has been termed the temperaturing indicating element and is connected to the indicating circuit. This resistance is very non-linear with themperature, being about 2,000 ohms at room temperature and 300 ohms at operating. The indicator adjustment has been set by comparison of indicator with actual sensing element resistance measurements.

Heating: The booster heater is used only to help bring the gyro quickly to operating temperature. The booster heater is automatically cut out by a thermostat set at 150 ± 5°F. Should the thermostat fail to open the temperature control unit relay will open the circuit at the control temperature. Operation of the booster thermostat can be observed by noting a

heater current drop as the gyro initially heats. The booster heater consists of 2-75 watt elements (150W). In this application this large boost is not recommended and current-limiting resistors are included in the temperature control unit.

The normal control heater consists of 3-25 watt elements (75W) meant to be controlled by the temperature control unit. A protective thermostat set at 170°F is in series with this heater.

Both heaters are intended to be served from a 28-volt D.C. source. As a convenience item, a nominal 24-volt A.C. source is used at present despite certain disadvantages.

Signal Generator:

Pattern field current: 50-200 ma. from a constant current source.

Signal frequency: min. 50 cps to several kilocycles.

Nominal field current: 100 ma. at 400 cps. The present system field current is about 130 ma.

Secondary (output) winding is designed to work into a high impedance load of 10^5 ohms or more.

Mechanical stops: $\pm$ 6°. These can only be detected at 6° when the gyro is operating at a temperature such that overall sensitivity is one degree output per degree input. At lower temperatures the apparent sensitivity will be lower.

Sensitivity: Nominally 34 millivolts rms per milliradian input with 100 ma, 400 cps, excitation current. The sensitivity may be approximated with ten per cent as 8.5×10^{-4} times the product of (excitation milliamperes and frequency in cps) for volts rms per radian input angle. See section 3.32.

Torque Generator:

Pattern field current: 10 to 200 ma. from a 5,000 ohm (or more) current source. Typical value 150 ma.

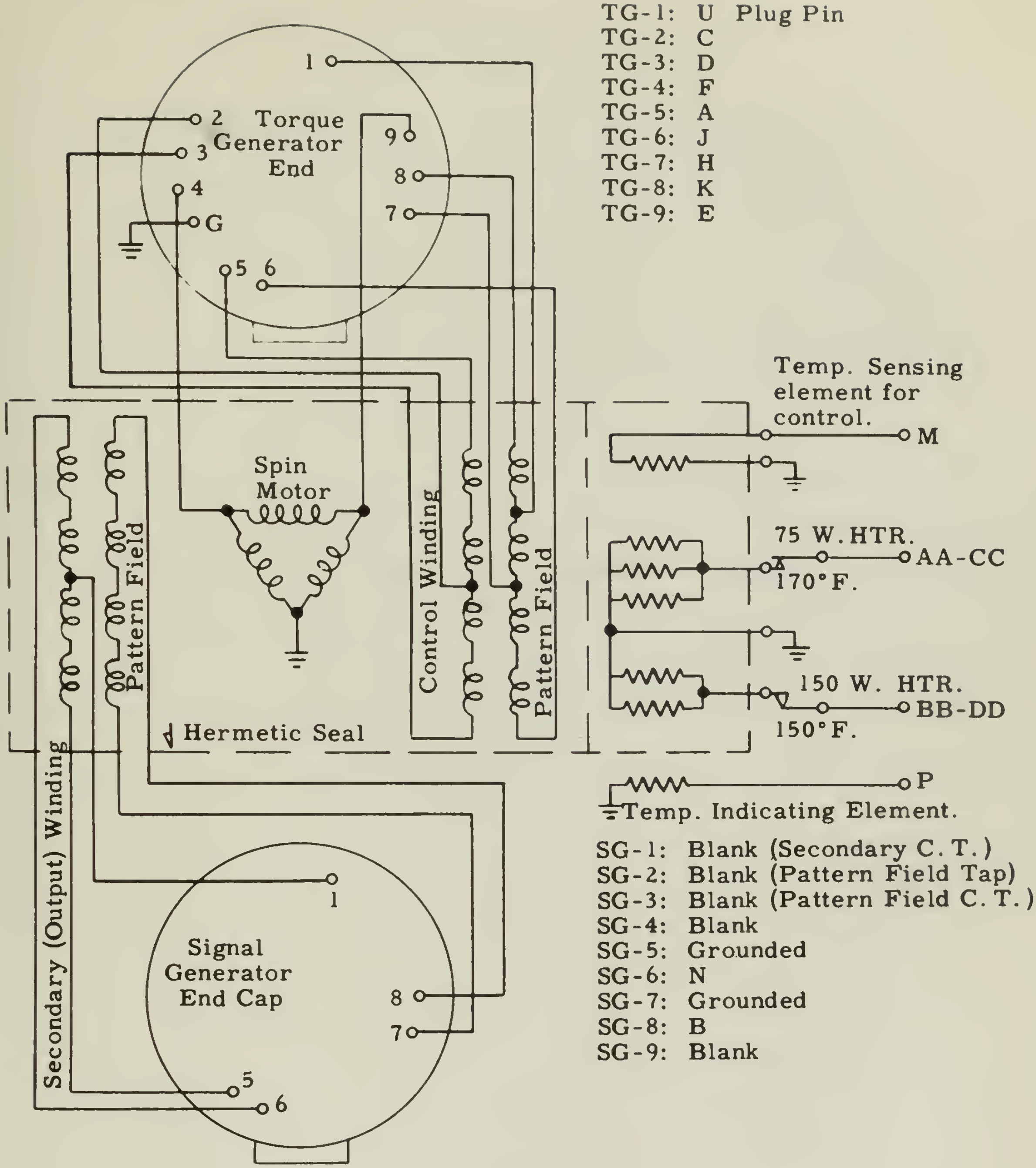


Figure C-I

HIG Wiring

Gyro Unit plug pin identification letters are shown.

at 400 cps.

Pattern field: resistance 100 to 135 ohms, inductance about 140 millihenrys.

Control field: 0-200 ma. Control resistance about 150 ohms, 150 millihenrys inductance.

Torque generated: nominally 2.5 times the product of field and control current in milliamperes; i.e., 2.5 dyne-cm per (milliamperes squared). A correction of (cosine phase angle) is appropriate if the two currents are not in phase. See 3.32.

<u>Zero-setting.</u> The torque generator will return the gyro to zero if the pair 5 and 6 and the pair 3 and 8 are cross-connected and the bridge is excited at pins 2 and 7. The loop gain is about 1.7×10^5 dyne-cm/radian, a relatively "weak spring." See Figure XIII. Faster response is obtained by using the feedback amplifier.

APPENDIX C-2

GYRO CASE

An assembly cross section and the location of mounting holes are shown in FiguresC-II, V and VI may be instructive. The gyro case is precision machined from aluminum and is black anodized to inhibit corrosion. The index positions are located at 0, 45 and 90 degrees precisely within a small part of one-tenth degree. The critical dimensions of the case are machined to compatible precision. Errors in orientation of the sensitive axis are thereby controlled. Performance errors due to orientation may ordinarily be proportional to the deviation of the cosine of the error angle from 1.000, and thus errors in the gyro case element are expected to be negligibly small for any future applications of the HIG Unit.

The HIG is clamped in aluminum rings to which protective thermoswitches are bonded. The aluminum rings are clamped in heat-insulating fibre rings. The fibre rings are held by machine screws within the case. The remaining annulus between HIG and case is filled with heat insulating styrofoam. All cabling is reeved through a stuffing tube at one end.

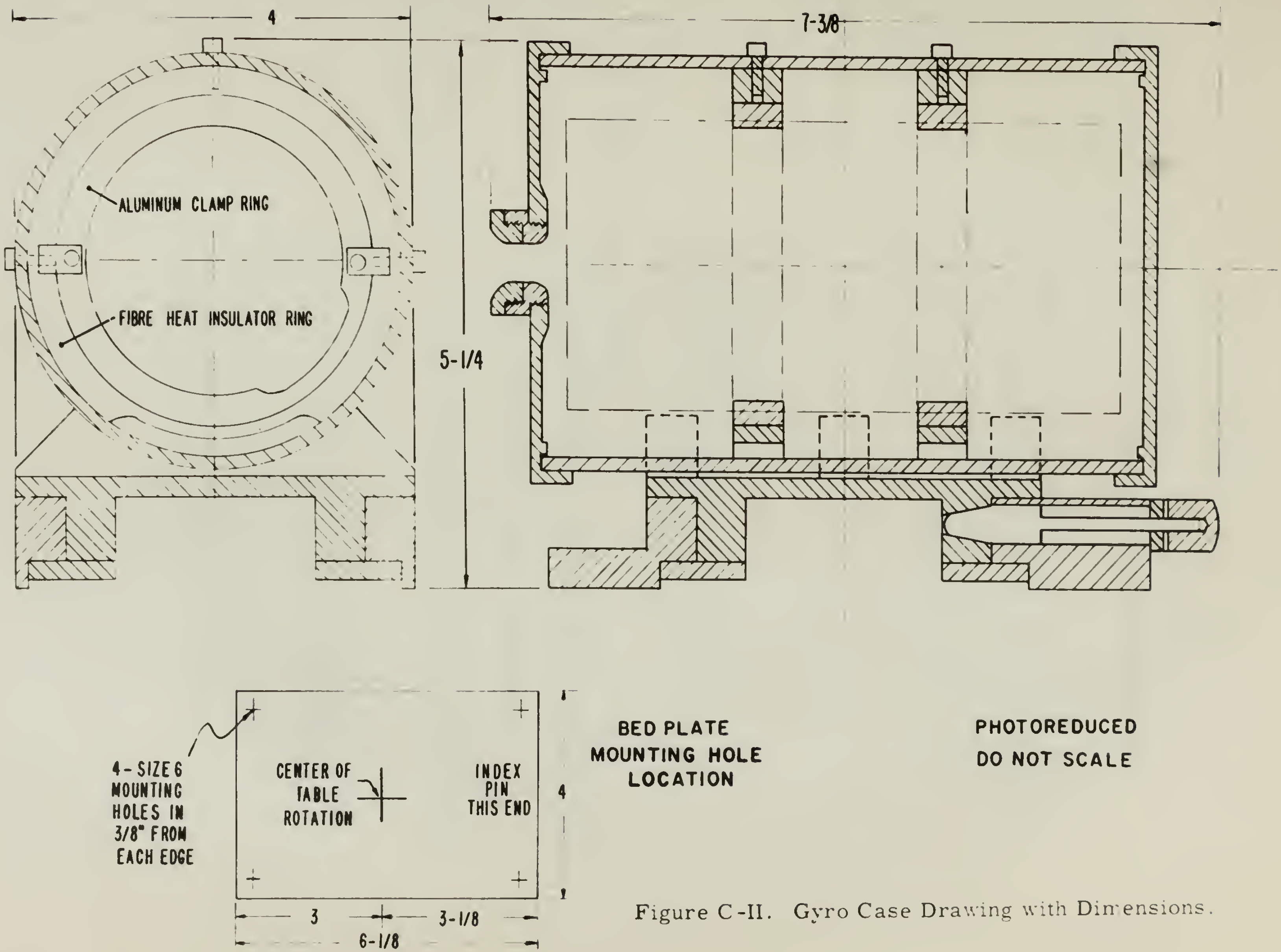


Figure C-II. Gyro Case Drawing with Dimensions.

APPENDIX C-3

JUNCTION BOX

The junction box wiring diagram circuit values are shown in Figure C-III.

The wiring of this unit should be considered principally as a convenience item and as one solution to the wiring problem that is suitable to the present conception of employment. Thus this unit could be replaced in other applications as long as the essential services are provided.

Wire Routing:

Gyro to Temperature Control:

150 W heaters
75 W heaters
Temperature measuring for control.
Temperature indicating circuit.
60 cps zero-set, when used.

Gyro to Power Supply:

Signal generator AC signal out, with resonating condenser.

Feedback Amplifier output, when used.

Distribution of 400 cps current received from the power supply unit, all to the gyro:

Spin motor.

Signal generator pattern field through a resonating network and current limiting resistance.

Torque generator pattern field drift compensating current when 60 cps caging is used.

Torque generator pattern field when amplifier caging or rate measuring.

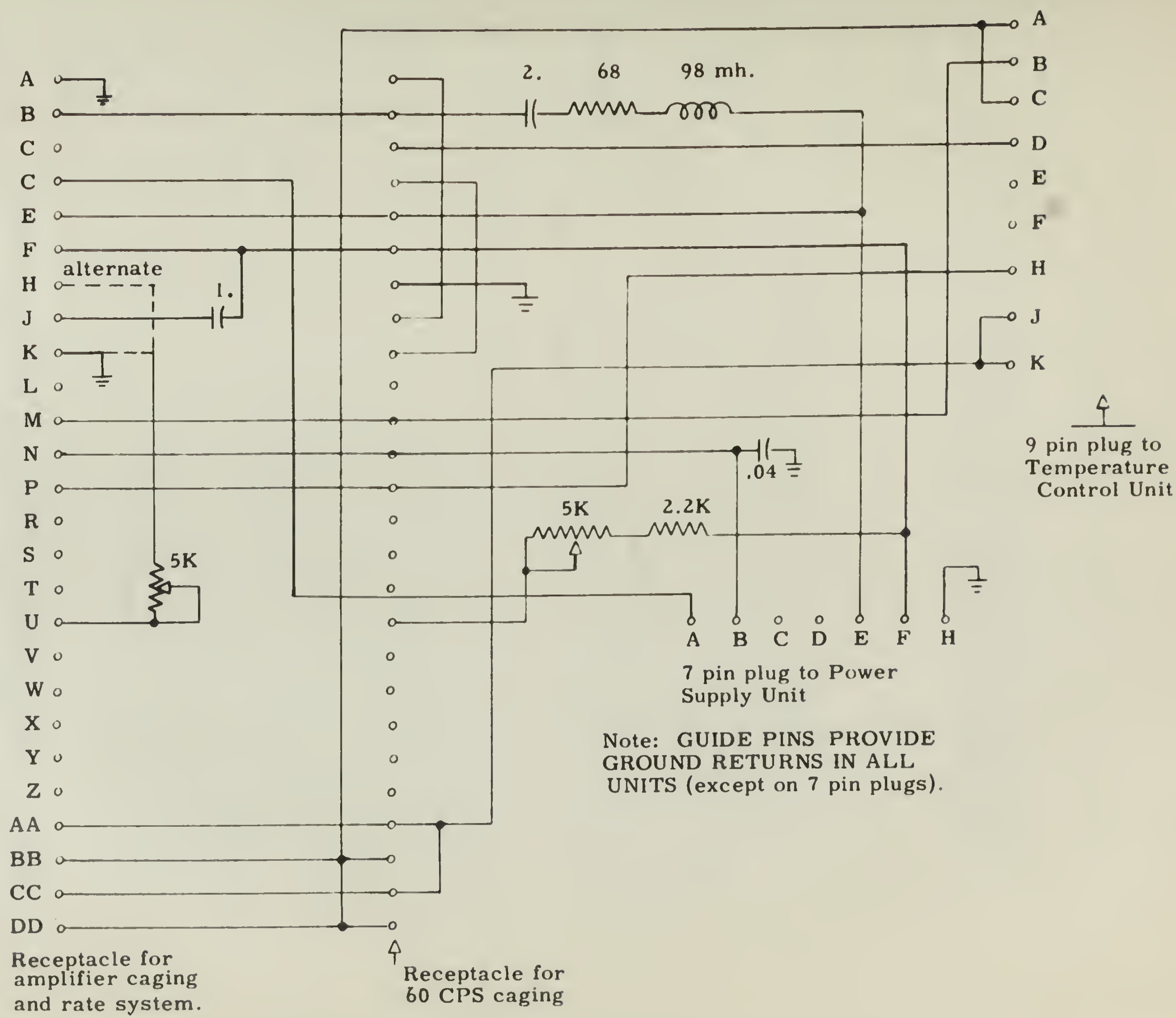


Figure C-III. Junction Box Wiring Diagram.

APPENDIX C-4

TEMPERATURE CONTROL

The circuit diagram of the Temperature Control Unit is shown in Figure C-IV. This Unit provides the following services.

1. Temperature Control.

The temperature sensing element of the gyro is connected as one arm of a resistance bridge excited by a 60 cps source. The bridge output is amplified by two sections of 12AX7 and delivered to the grid of a 2D21 thyratron. The thyratron plate circuit is fed from an AC source through a 10,000 ohm relay. The amplifier is phased such that low sensing resistance (low gyro temperature) closes the heating current circuit.

2. Heating Current Source.

The gyro heaters are intended for a 28-volt DC source. Such a source when available should be connected to an appropriate terminal at the rear of the chassis. In the absence of this source, a 24-volt AC source is provided and jumpered to the proper terminal. A switch will interrupt the availability of heater power. Availability of power is indicated by a green pilot. This switch is considered a prudent necessity. It interrupts the heating power whenever the temperature sensing element is switched out of the control bridge, as may be done for accurate temperature readings.

3. Accurate temperature measurement.

The reference for temperature measurement is the resistance of the sensing element. This is adjusted by the manufacturer to be 780 ohms at operating temperature. The resistance element can not be measured conveniently while in the control bridge. Therefore provision is made to switch out the element and enable a resistance measurement by a wheatstone bridge at a terminal at the rear of the chassis and ground (chassis). Switching out

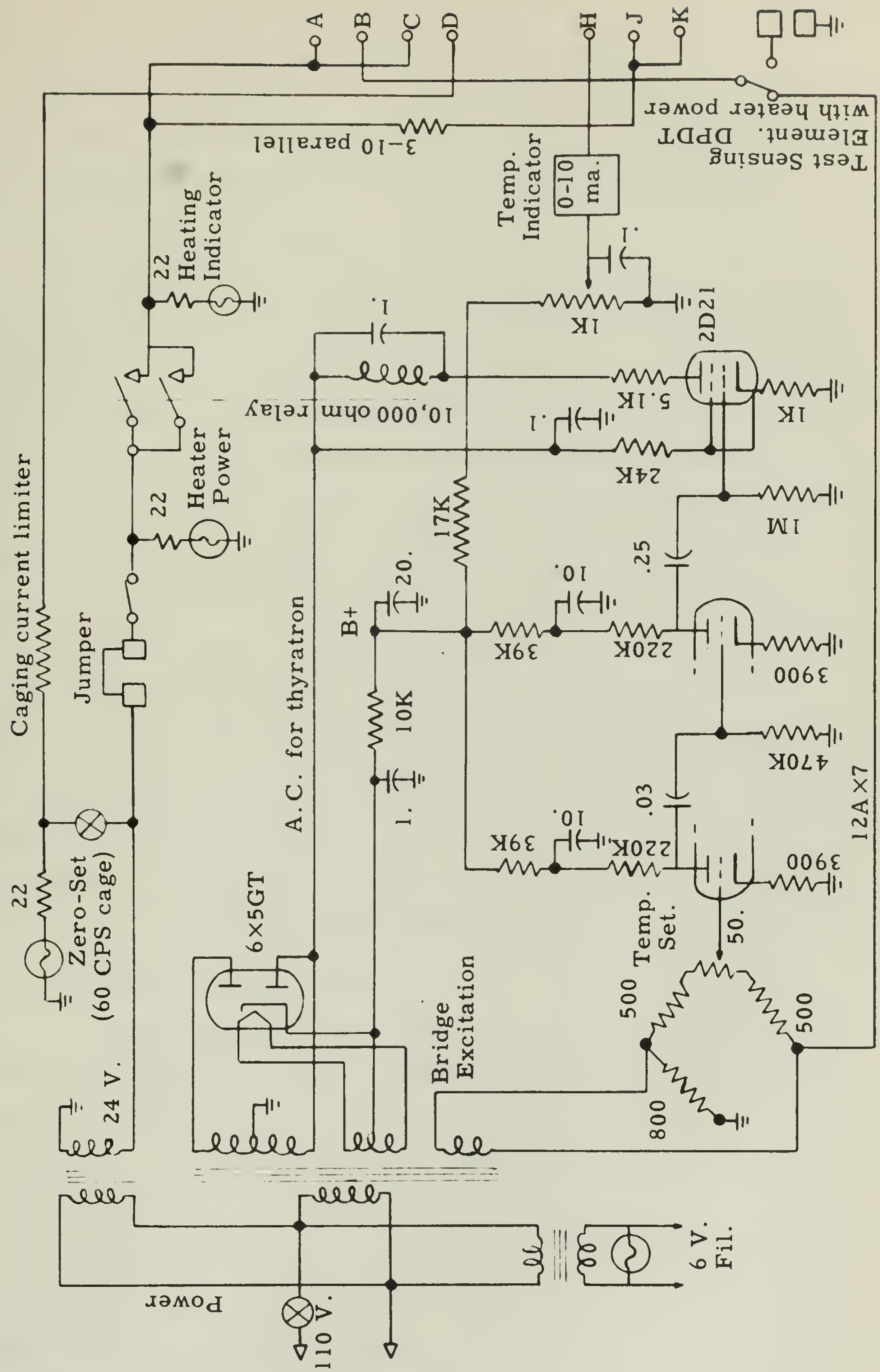


Figure C-IV. Temperature Control Unit Wiring Diagram.

the resistance element also interrupts the heater power source to prevent any possibility of gyro overheating. The common switch is labelled "Heater Power." This resistance element should be used in all cases requiring actual temperature measurement. As a convenience an independent indicating system is provided.

4. Temperature Indicating.

As a convenient indicator and independent approximate temperature check, an independent non-linear resistance element (Thermistor type 32A12, Victory Engineering Corporation) has been thermally and mechanically bonded to one gyro clamp ring. The resistance of this element varies from about 2,000 ohms at room temperature to about 300 ohms when the gyro is at its correct operating temperature as indicated by the temperature reference element. Using the resistance of the temperature (sensing) reference element as a standard, the indicating circuit current can be adjusted to cause the indicating meter (0-10 milliamperes) to read at the "operating" calibration (about 5 milliamperes). The meter may then be used as a convenient indicator of gyro temperature and on-off operation of the control unit may generally be expected to mean the gyro temperature is being properly controlled. In all cases of doubt or fundamental inquiry of temperature dependence, resort must be made to the procedure of accurate temperature measurement described in section (4).

5. 60 CPS Zero-setting (caging).

It is possible to cross-connect the two torque generator windings and provide excitation at the two winding center-taps to return the gyro to a position of symmetry, which is the zero-reference. The torque generator is operating in this case like a centering spring. Provision is made in the junction box to do this cross-connection when the "60 CPS Zero-Set" receptable for the gyro plug is used. In this case 60 CPS current is taken from the 24 volt AC heater source through a "Gyro Free - 60 CPS Zero-Set" switch with red pilot in the Temperature Control Unit. Notice the torque generator is NOT connected directly to 24 VAC but is

current-limited by a series resistor. 24 VAC direct will burn out the torque generator windings. A maximum of about 100 milliamperes per winding is employed here.

This method of zero set will be adequate for many purposes. The effective spring constant is much less in this manner of connection compared with using the feedback amplifier discussed elsewhere.

APPENDIX C-5

POWER SUPPLY UNIT

The circuit diagram of this unit is shown in Figure C-V. This unit provides the following services.

1. 400 CPS-3-Phase Power Source.

A vibrator supply is used to supply 400 CPS 3-Phase power to the gyro spin motor. In the absence of any other source this may also be used for the AC signal circuits. At various points in this unit and the Junction Box, 400 CPS current is taken from one phase referred to the grounded phase.

2. Signal Demodulation.

The AC signal from the gyro is received in this unit via the Junction Box. The AC signal is converted to DC in a phase-sensitive detector in the form of a synchronous converter (chopper). This is a vibrating reed device whose reed excitation (electromagnet) is phased by an RC network. The chopper output is passed through an RC low-pass filter. At the DC output test point the signal is now a DC voltage whose magnitude and polarity indicate magnitude and sense of the gyro output. The gyro output signal may be proportional to angle or rate. This is a high impedance output and not suitable for reading or recording by low impedance instruments.

3. Feedback Amplifier Connection.

The Feedback Amplifier receives its input, the gyro signal output, from the Power Supply Unit. The output of the Feedback Amplifier is switched either to a dummy load resistor or to the gyro torque control field winding. The gyro is free and not zero-set when the amplifier is switched to a dummy load. The gyro will tend to zero when its output is amplified and fed back, or the gyro may be used to measure angular rates with this connection.

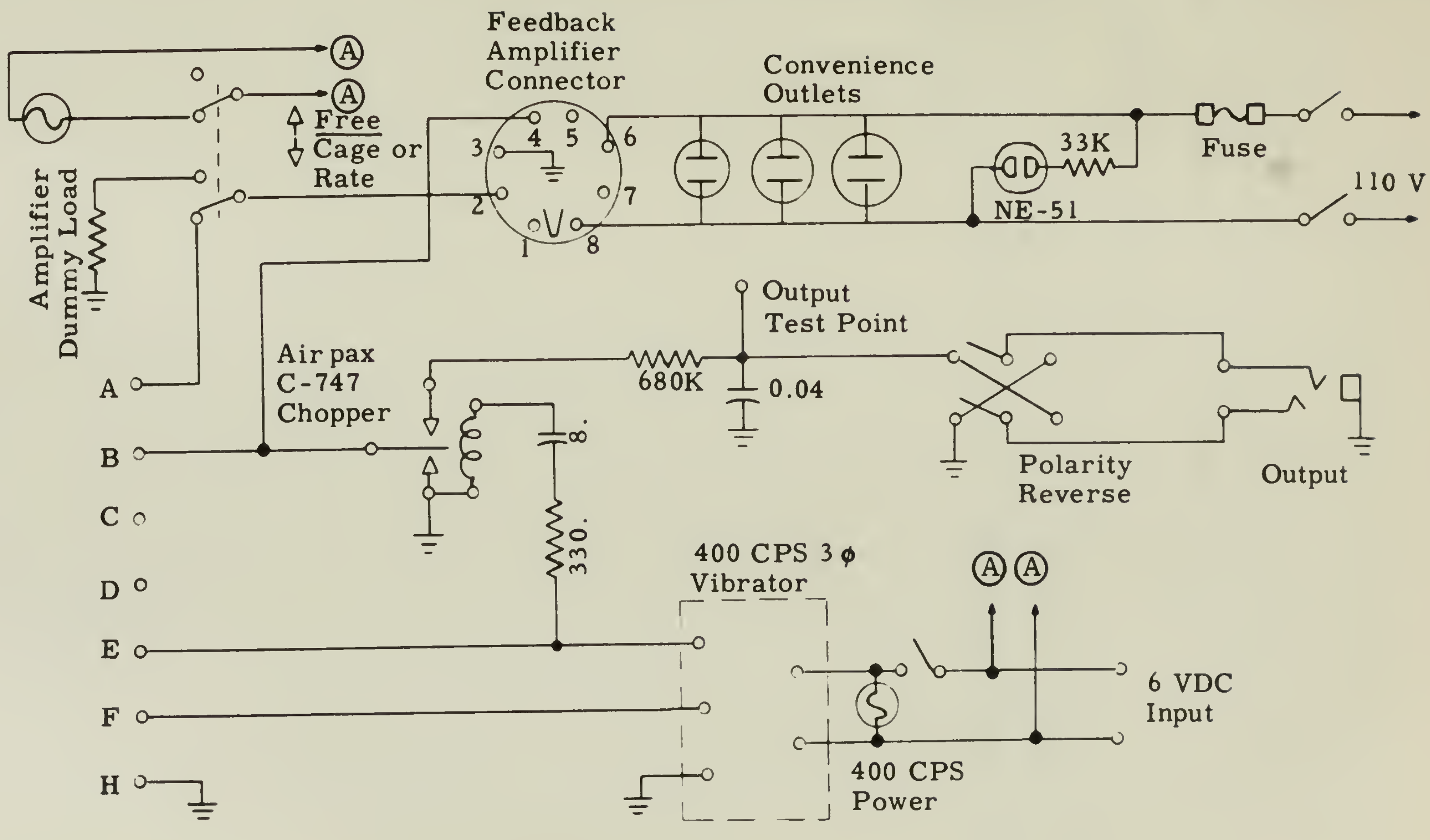


Figure C-V. Power Supply Unit Wiring Diagram.

4. Convenience Outlets.

Convenience outlets are provided at the rear of the Power Supply Unit. Other units of the system may be powered from here and controlled from this power switch. One of these outlets is particularly suited for the battery charger which is used as primary power for the vibrator supply.

5. Recorder Connection.

A telephone jack (3 terminal) is provided for connection to the recording equipment. Prior to this connection is a polarity-reversing switch to change deflection direction of the recording pen.

APPENDIX C-6

THE FEEDBACK AMPLIFIER

The wiring diagram of the feedback amplifier is shown in Figure C-VI. This unit when used is intended to be connected to the Power Supply Unit. A single connecting cable is used. The amplifier receives primary power and gyro AC output signal from the Power Supply Unit. The amplifier output is sent to the gyro torque generator control winding via the Power Supply Unit and Junction Box. The feedback path is thus closed providing the zero-set or rate switch is closed (on the Power Supply Unit) and the Feedback Amplifier receptacle on the Junction Box is used.

The amplifier output and the torque generator pattern field excitation should be phased to obtain maximum torque. Refer to section 3.32. The overall phasing of signal generator excitation and output, amplifier output, and torque generator current directions must provide negative feedback or the gyro will be driven into the mechanical stops. Correct phasing will center (zero-set) the signal generator to zero output in the absence of rate inputs.

The amplifier consists of a 12AX7 voltage amplifier-phase splitter to drive the push-pull 6AQ5 pentodes. The variable feedback to the 12AX7 can be used to change gain. The bias of the 6AQ5 tubes may be adjusted if a particular gain-linearity situation arises, which is not immediately likely for all signal voltages should be small.

The amplifier can deliver perhaps 100 ma or more to the gyro control winding but such large currents would indicate large angular rates to the gyro. The amplifier gain can be typically 1 milliamperes control current per millivolt input signal. With typical torque and signal generator sensitivities, this is sufficient for loop gains of around 10^7 dyne cm/radian.

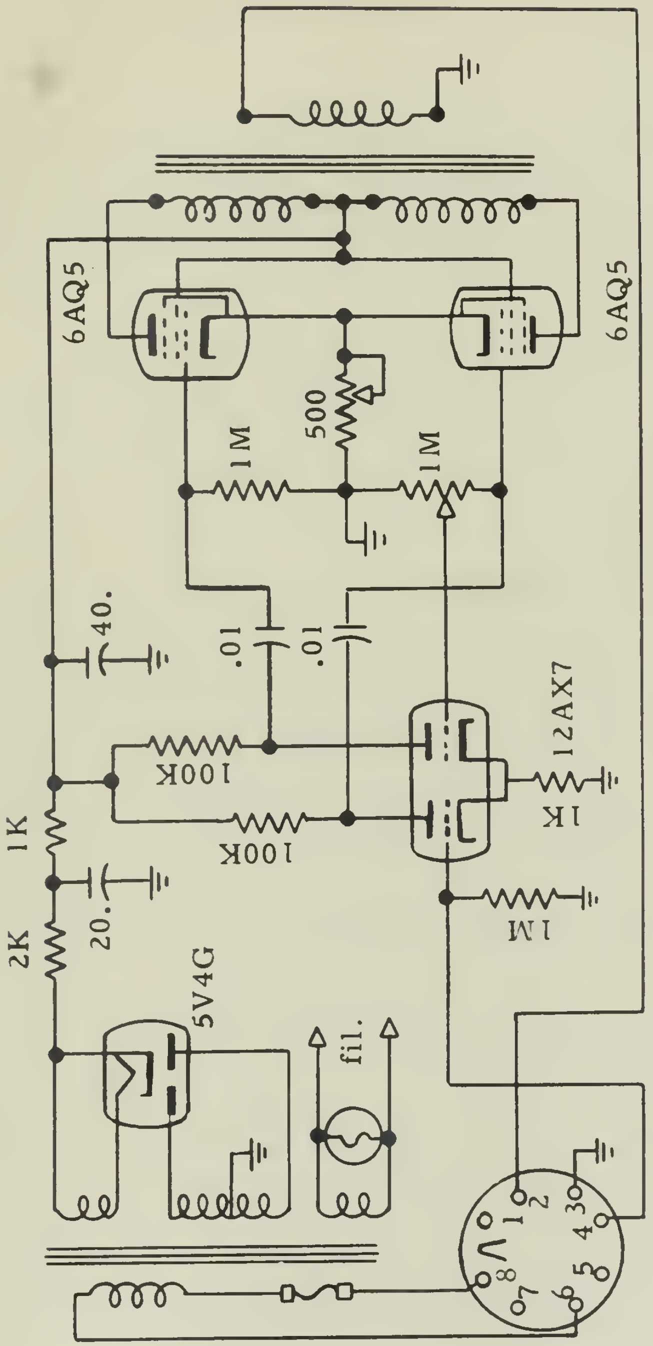


Figure C-VI. Feedback Amplifier Unit Wiring Diagram.

APPENDIX D

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